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to
Department of Fisheries and Oceans
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DERIVATION AND ANALYSIS OF A MODEL
TO PREDICT THE EFFECT OF
ACIDIC DEPOSITION ON SURFACE WATERS

by

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I INTRODUCTION

Over the past four years, ESSA Ltd. has assisted the Canadian Department of Fisheries and Oceans (DFO) in the development and analysis of a regional model to explore the effects of acidic deposition on fisheries resources. The model has proven to be a useful tool for estimating large scale impacts and evaluating the consequences of various emission control scenarios. Recently, both DFO and Environment Canada have indicated interest in using the model to assess the effects of proposed emission control policies on surface waters. To achieve this goal in a scientifically credible manner, these two agencies have contracted ESSA Ltd. to review, incorporate further refinements, and finally re-apply the regional model to eastern Canada. This report summarizes the results of the contracted work.

The process of model refinement and analysis is an ongoing one, and it would be unrealistic to assume, from a scientific standpoint, that it is ever complete. Decision makers and negotiators do not have open-ended time horizons, however, and therefore demand defensible results as quickly as possible. Over the past 10 months we have carried out a number of tasks leading to the preparation of regional estimates of the impacts of four acidic deposition scenarios (derived from emission scenarios using the AES transport and deposition model) on surface water chemistry in eastern Canada. These tasks can be grouped into three major

categories:

- 1) Refining the water chemistry model, based on discussions with leading researchers on acidic deposition and its effects on surface waters;
- 2) Reviewing model input data and supplementing or replacing these data where appropriate; and
- 3) Developing and applying to the model four scenarios of acidic deposition, based on the application or lack thereof of emission control strategies, to produce regional impact estimates.

The report contains a section devoted to each of these three sets of tasks. In section 2 we describe the derivation of the water chemistry model, based on a manuscript currently in preparation. The model's structure is significantly changed from that presented in an earlier report (Jones et al. 1984), although the basic premises that underlie its derivation remain the same. Section 3 describes the data used as inputs to the model, documents their sources and comments on the major assumptions required to use the data. Section 4 presents the results of the study in the form of predicted eventual chemical conditions for 38 secondary watersheds in eastern Canada south of 52°N latitude, given four different scenarios of future acid sulphate emissions.

1.1 Overview of the Regional Model

The overall model consists of both a single lake, site model and a multiple lake, regional model (Figure 1.1). The site model consists of a set of equations to predict the

Regionalization

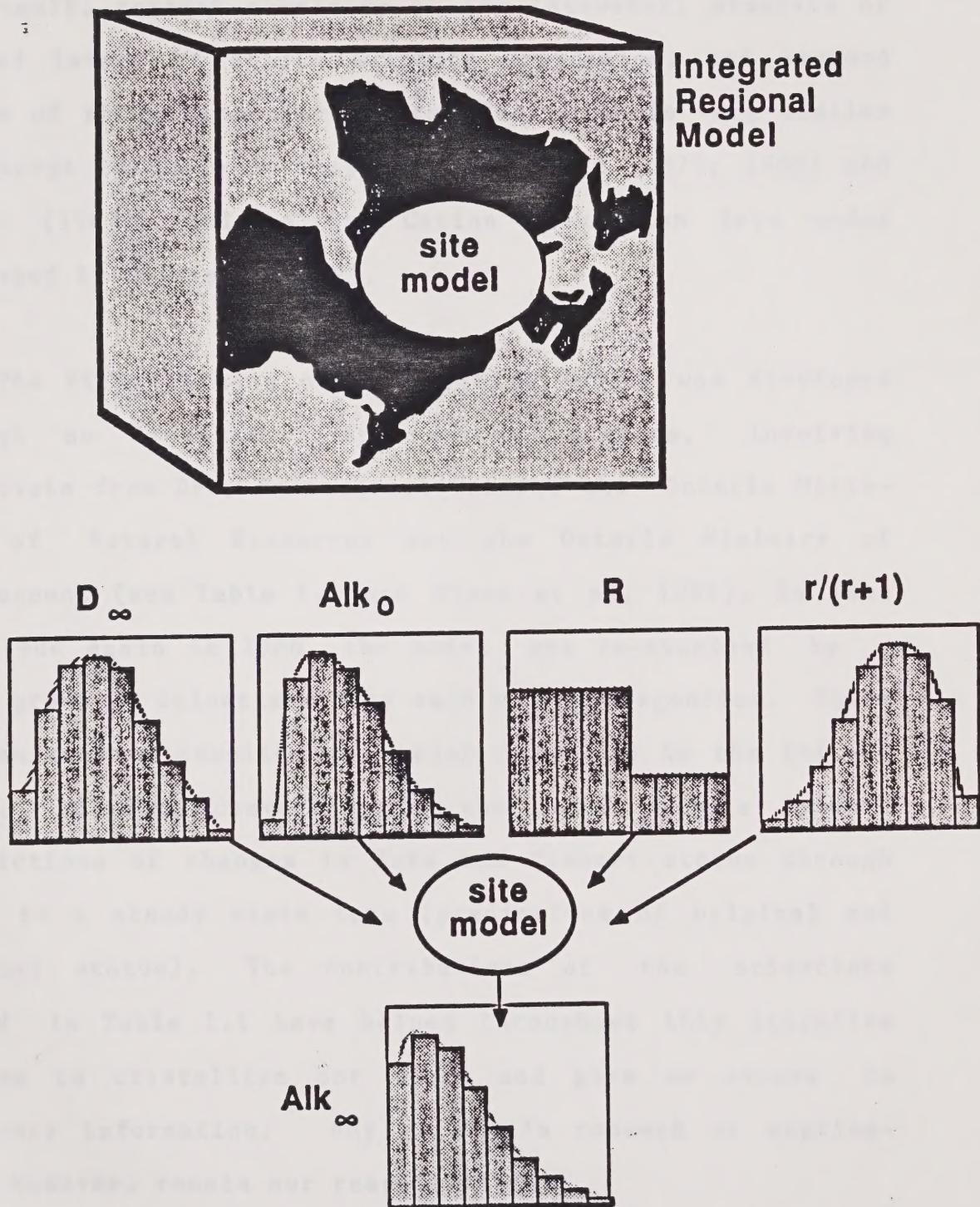


Figure 1.1: Overall structure of the regional model. The site model calculates the eventual pH of a single lake, given a set of input parameters. The regional model integrates over all observed parameter combinations, and generates a frequency distribution of eventual pH.

eventual chemical status of a single lake (alkalinity, pH, cations, and sulphate), based on its watershed's morphometry and runoff, current chemistry of the lakewater, observed or assumed levels of acidic sulphate deposition, and assumed values of three other parameters. The model is very similar in concept to those developed by Henriksen (1979; 1980) and Wright (1983), and to the Cation Denudation Rate model developed by Thompson (1982).

The first version of the regional model was developed through an iterative, interactive process, involving scientists from DFO, Environment Canada, the Ontario Ministry of Natural Resources and the Ontario Ministry of Environment (see Table 1.1 and Minns et al. 1986). In late 1983, and again in 1986, the model was re-examined by a small group of scientists from each of these agencies. These re-examinations resulted in major revisions to the initial model, including conversion of the model from a dynamic (predictions of changes in lake and fishery status through time) to a steady state form (predictions of original and eventual status). The contributions of the scientists listed in Table 1.1 have helped throughout this iterative process to crystallize our ideas and give us access to necessary information. Any errors in concept or application, however, remain our responsibility.

Table 1.1: Scientists who contributed to the development and application of the model.

<u>Name</u>	<u>Organization</u>
Paul Arp	UNB, Fredericton
Gail Beggs	OMNR, Toronto
Willie Bruce	DFO, St. John's, Newfoundland
Nels Conroy	OME, Sudbury
John Cooley	DFO, Burlington
Peter Dillon	OME, Dorset
Floyd Elder	DOE, Burlington
Andy Fraser	DOE, Burlington
Jan Gray	DFO, Sault Ste. Marie
Harold Harvey	Zoology Department, University of Toronto
Robert Helie	DOE, Ottawa
Ray Hesslein	DFO, Winnipeg
Dean Jeffries	DOE, Burlington
Murray Johnson	DFO, Owen Sound
Bill Keller	OME, Sudbury
John Kelso	DFO, Sault Ste. Marie
Joe Kerekes	DOE, Halifax
Marius LaChance	INRS, Eau, University of Quebec
David Lam	DOE, Burlington
Bruce LaZerte	OME, Dorset
Jim MacLean	OMNR, Algonquin Park
Greg McCullough	DFO, Winnipeg
Ken Mills	DFO, Winnipeg
Ken Minns	DFO, Burlington
Marv Olson	AES, Downsview
Madeleine Papineau	DOE, Quebec
Dick Peterson	DFO, St. Andrews
Roger Pitblado	Laurentian University, Sudbury
Dick Ryder	OMNR, Thunder Bay
Wolfgang Scheider	OME, Toronto
David Scruton	DFO, St. John's, Newfoundland
Michael Staley	ESSA Ltd., Vancouver
Peter Summers	AES, Downsview
Michael Turner	DFO, Winnipeg
Sandy Verry	USFS, Grand Rapids, Minnesota
Yvan Vigneault	DFO, Quebec City
Donna Wales	OMNR, Toronto
Walton Watt	DFO, Halifax
Wesley White	DFO, Halifax
Richard Wright	NIVA, Oslo, Norway

II DERIVATION OF THE SITE MODEL

2.1 Introduction

In the following derivation, we present only those equations used to calculate eventual alkalinity and pH, since these are the two lake chemical variables of primary interest to the lake acidification issue. Calculations of eventual cation and sulphate concentrations are very similar to the alkalinity calculations.

The site model can be most simply represented as the equation:

$$(1) \quad \text{Alk}_{\infty} = \text{Alk}_0 - \Delta \text{Alk}$$

(All the terms in this and subsequent equations are defined in Table 2.1). The derivation thus consists of three steps:

- 1) Describing the change in alkalinity due to acidic deposition (ΔAlk), as a function of the assumed level of deposition, and estimated levels of acid neutralization within both the terrestrial watershed and the lake.
- 2) Describing the lake's original alkalinity (Alk_0) as a function of its current chemistry, the chemistry of lakes of similar geochemistry but with low levels of acidic deposition (reference areas), and non-acidic sulphate deposition.
- 3) Combining steps 1 and 2 in equation (1) so that the eventual alkalinity (Alk_{∞}) resulting from a prescribed level of acidic deposition can be predicted.

An important feature of the model is its representation

Table 2.1: Definitions of terms and subscripts used in equations. see text for further explanation.

Variable	Description	Units
A_o	Lake area	m^2
A_w	Total drainage area (excluding lake)	m^2
Alk	mean lake alkalinity	$\mu eq.L^{-1}$
C	Total base cation concentration	$\mu eq.L^{-1}$
D	Acidic sulphate deposition	$meq.m^2.yr^{-1}$
F	Cation exchange factor	none
F_w	Watershed neutralization	none
F_l	Lake neutralization	none
Q	Volume of lake outflow	$m^3.yr^{-1}$
R	Runoff	$m.yr^{-1}$
S_s	Mass transfer coefficient	$m.yr^{-1}$
a,b	Parameters of F_w -Alk _o relationship	$\mu eq.L^{-1}$
r	A_w/A_o	none
z	Lake mean depth	m
τ	Water residence time	yr

of time. In deriving the site model equations, we considered the state of the system at three times: originally ($t=0$), currently ($t=t$), and eventually ($t=\infty$). The model has no quantitative time scale: $t=0$ is the period prior to acidification, when acidic deposition is assumed to be zero; $t=t$ is the time during which lake chemistry samples (the primary input data) were taken; and $t=\infty$ describes the time when the watershed and lake are at steady state with respect to the assumed level of acidic deposition. If the lake's current chemistry is close to steady state with respect to deposition, then the predicted eventual condition will be close to that which is currently observed.

2.2 Calculation of Alkalinity

Lake cation and alkalinity concentrations are affected by a complex combination of watershed chemical and biological processes (NRCC 1981; Stumm et al. 1983). Any model of acidification must include some representation of these processes. We chose to represent the level of neutralization of acidic deposition within the terrestrial watershed as the fraction of total deposition per unit area neutralized (F_w , a number between 0 and 1). Within-lake neutralization of acidity is treated in a similar manner: the fraction of acidity reaching the lake which is subsequently neutralized is represented by F_l , also a number between 0 and 1. The deposited acidity which is not neutralized, and therefore creates a change in lake alkalinity, can be represented by:

$$(2) \quad \Delta \text{Alk} = \frac{A_o D_\infty + A_w D_\infty (1-F_w)}{Q} (1-F_1)$$

Equation (2) assumes that F_w applies only to the deposition falling directly on the terrestrial watershed. The remaining acidity, exported to the lake and mixed with acidity falling directly on the lake, is diluted by runoff and is subject to neutralization by in-lake processes (the $(1-F_1)$ term).

Replacing Q by $(A_w + A_o)R$ (where R is the mean annual runoff (m.yr^{-1})) and then rearranging terms, one obtains:

$$(3) \quad \Delta \text{Alk} = \left[\frac{D_\infty}{R} - 1 - \left(\frac{r}{r+1} \right) F_w \right] (1 - F_1)$$

The term $r/(r+1)$ is equivalent to $A_w/(A_w + A_o)$ where $r = A_w/A_o$.

Of the five variables in equation (3), two are relatively easily obtained from existing data: R and r (see Section 3). Acidic deposition, D_∞ , is either set as a control variable to simulate changes in deposition, or for current deposition, is computed from wet sulphate deposition plus estimated dry deposition, minus sulphate contributed by sea-spray or deposited prairie dust (section 3.7).

The value for F_w is assumed to be zero below some minimum value of Alk_0 (a) and increase linearly with Alk_0 up to a maximum value of one at some higher Alk_0 value (b). That is:

$$\begin{aligned} F_w &= 0. & , \text{ for } Alk_0 \leq a \\ (4) \quad F_w &= \frac{Alk_0 - a}{(b-a)} & , \text{ for } a < Alk_0 < b \\ F_w &= 1. & , \text{ for } Alk_0 \geq b. \end{aligned}$$

The rationale for this assumption is that the watershed properties which are generally associated with low alkalinity surface waters, such as short soil contact time and low base saturation of soils (Schofield 1984), would also tend to reduce the proportion of acidity neutralized in the watershed (F_w). Note that use of a constant F_w value greater than zero implies that a watershed can never have its acid neutralization capacity completely exhausted. The method of computing Alk_0 is described below.

There are unfortunately very few data for confirming the assumed values for F_w , a and b, though the work of Henriksen (1982) offers some guidance. Henriksen (1982) suggested that as acidic deposition increases, lake cation concentrations should increase (due to cation exchange in watershed soils), and that the change in lake base cation concentrations from the lake's original to its current condition should be proportional to the change in lake

sulphate concentrations. He proposed an "F-factor", described by:

$$(5) \quad F = \frac{[Ca + Mg]_t - [Ca + Mg]_0}{[SO_4]_t - [SO_4]_0}$$

which has approximately the same effect functionally in his model (see Henriksen 1982; Wright 1983), as F_w does in ours. Henriksen (1982) estimated that F varied from 0.0 to 0.4 within sensitive Norwegian lakes, while time series data from Swan Lake in the Sudbury Area of Ontario (where both sulphate and base cation concentrations have decreased) indicates that F may be as high as 0.64 (Dillon et al. 1986). The assumption that F_w varies with Alk_0 is consistent with the output of 140-year simulations using a process-oriented model (Wright et al. 1986), which indicated that the Henriksen "F-factor" increased from 0.3 to 0.6, as original cation concentrations increased from 5 to 50 $\mu\text{eq L}^{-1}$. In our simulations we have held the value of "a" in equation (4) at 0 $\mu\text{eq L}^{-1}$, and examined the effect of varying "b" from 200 to 1000 $\mu\text{eq L}^{-1}$.

The final parameter in equation (3) is F_1 . Here we assume that all in-lake alkalinity generation is due to sulphate retention, and use the formulation developed by Kelly et al. (1986) for estimating the proportion of sulphate retained:

$$(6) \quad F_1 = \frac{S_s}{(z/\tau) + S_s}$$

The term (z/τ) is equivalent to areal outflow (Q/A_o) , or $R (r+1)$, which can be substituted into equation (6) to obtain:

$$(7) \quad F_1 = \frac{S_s}{R (r+1) + S_s}$$

Substituting equation (7) into equation (3) yields an overall expression for the change in alkalinity due to acidic deposition:

$$(8) \quad \Delta \text{Alk} = \frac{D_\infty}{R} \left[1 - \left(\frac{r}{r+1} \right) F_w \right] \left[1 - \frac{S_s}{R (r+1) + S_s} \right]$$

2.3 Calculation of Original Alkalinity

Alkalinity is generally defined as the equivalent sum of all the bases that can be titrated with strong acid to a preselected equivalence point (Stumm and Morgan 1981), or:

$$(9) \quad \text{Alk} = [\text{HCO}_3^-] + [\text{CO}_3^{2-}] + [\text{OH}^-] + [\text{RCOO}^-] - [\text{H}^+]$$

where all concentrations are in equivalents. An alternate

equation, which is approximately equivalent to equation (9), can be derived by grouping together the remaining cations and anions (Driscoll et al. 1986):

$$(10) \quad \text{Alk} = [\text{C}] + [\text{NH}_4^+] + [\text{Al}^*] - [\text{SO}_4^{2-}] - [\text{NO}_3^-] \\ - [\text{Cl}^-] - [\text{F}^-]$$

where C equals the sum of base cations (Ca+Mg+Na+K), and Al* represents various forms of aluminum with different valences. In the absence of acidic conditions, it can be assumed that aluminum makes a negligible contribution to alkalinity. We further assume that the quantity $([\text{NH}_4^+] - [\text{NO}_3^-] - [\text{F}^-])$ is close to zero. We therefore arrive at the following expression for original alkalinity:

$$(11) \quad \text{Alk}_0 = [\text{C}]_0 - [\text{Cl}]_0 - [\text{SO}_4]_0$$

Original cation concentrations, the first term in equation (11), can be estimated from current cation concentrations after correcting for increases during the period of acidic deposition due to cation exchange. Taking equation (5), replacing (Ca + Mg) by C and rearranging terms, yields:

$$(12) \quad [\text{C}]_0 = [\text{C}]_t - F \left[[\text{SO}_4]_t - [\text{SO}_4]_0 \right]$$

This is the method used by Wright (1983), which we have modified slightly. We replace F by $F_w [r/(r+1)]$,

since we have assumed that F_w applies only to the terrestrial watershed. Under this formulation watersheds with larger watershed to lake area ratios yield larger shifts in cation concentrations. Our model therefore assumes that no cation exchange occurs in the lake. Even though cation exchange reactions have been observed in lake sediments and may be an important buffering reserve (Oliver and Kelso 1982; Schindler et al. 1986), they are of greater quantitative importance after the lake has begun to acidify. Substituting the modified expression for C_0 into equation (11) yields:

$$(13) \quad \text{Alk}_0 = [C]_t - F_w \left(\frac{r}{r+1} \right) \left[[SO_4]_t - [SO_4]_0 \right] - [Cl] - [SO_4]_0$$

2.4 Calculation of Eventual Alkalinity

We now have expressions for the two terms on the right hand side of equation (1). Substituting equations (8) and (13) into equation (1) yields an overall expression for eventual alkalinity:

$$(14) \quad \text{Alk} = C_t - F_w \left(\frac{r}{r+1} \right) \left[[SO_4]_t - [SO_4]_0 \right] - [Cl]_0 - [SO_4]_0 - \frac{D_\infty}{R} \left[1 - \left(\frac{r}{r+1} \right) F_w \right] \left[1 - \frac{S_s}{R(r+1) + S_s} \right]$$

2.5 Calculation of pH from Alkalinity

The functional relationship between the alkalinity and pH of an aqueous solution can be described by equation (9) (Stumm and Morgan 1981):

$$(9) \quad \text{Alk} = [\text{HCO}_3^-] + [\text{CO}_3^{2-}] + [\text{OH}^-] + [\text{RCOO}^-] - [\text{H}^+]$$

Given assumed values for the relevant dissociation constants, one can use numerical methods to solve this equation for the $[\text{H}^+]$ associated with any alkalinity. We have used equation (9) to derive a theoretical titration curve for predicting pH from alkalinity, based on the assumptions that the contribution of organic anions (RCOO term) is negligible, and that $\text{pCO}_2 = 2.8$. The results of applying this theoretical titration to the National Inventory Survey dataset (Kelso et al. 1986) and a subset of the U.S.E.P.A. Eastern Lake Survey dataset are presented in Figures 2.1-2.2.

The model fits the data quite well in both cases, suggesting that our assumptions regarding the importance of organic anions and the value of pCO_2 are not unreasonable. Poorer fits were obtained when pCO_2 values of 2.5, 3.0, and 3.5 were tried. Further evidence in support of ignoring organic anions in this regional analysis comes from an examination of the relationship between the residuals from our theoretical model and the observed DOC of the lakes in the Eastern Lake Survey dataset (Figure 2.3). The relationship, though statistically significant, is very weak ($r^2 = .116$).

National Inventory Survey

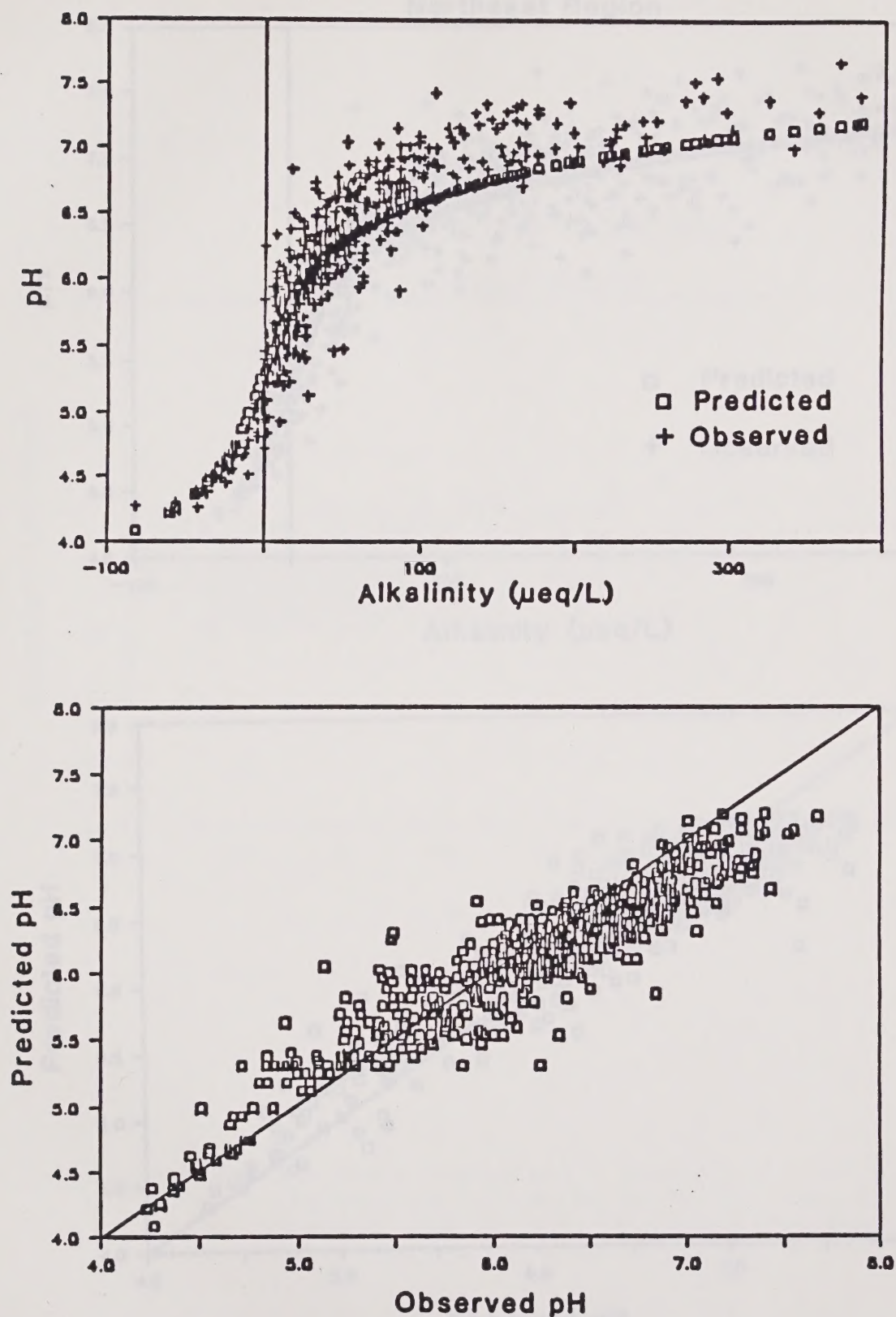


Figure 2.1: Predicted and observed pH from alkalinity for the National Inventory Survey dataset ($n = 615$ lakes). Only lakes with alkalinities $< 400 \mu\text{eq.L}^{-2}$ were included.

Eastern Lake Survey

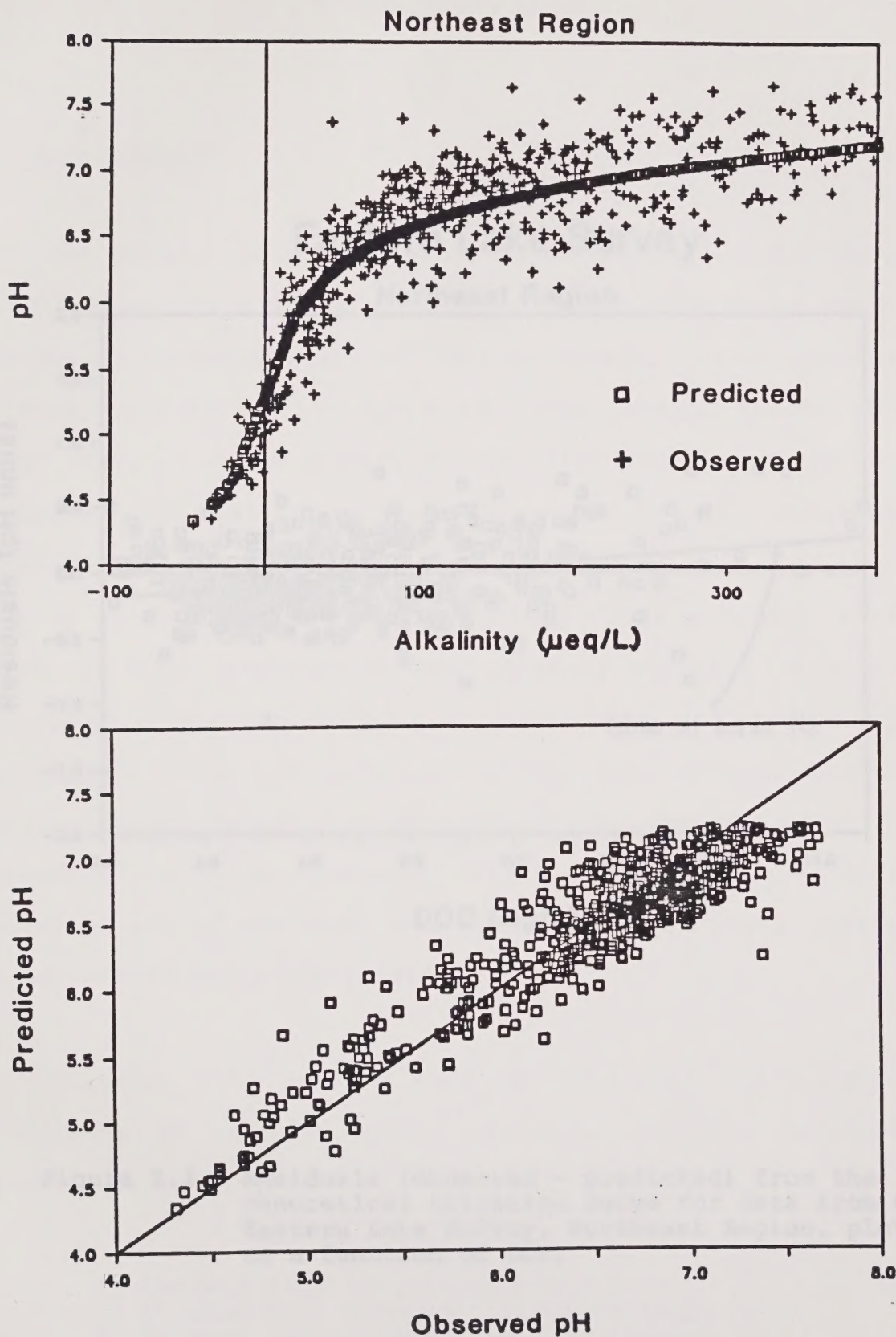


Figure 2.2: Predicted and observed pH from alkalinity for the Eastern Lake Survey, Northeast Region dataset ($n=660$ lakes). Only lakes with alkalinities $< 400 \mu\text{eq.L}^{-2}$ were included.

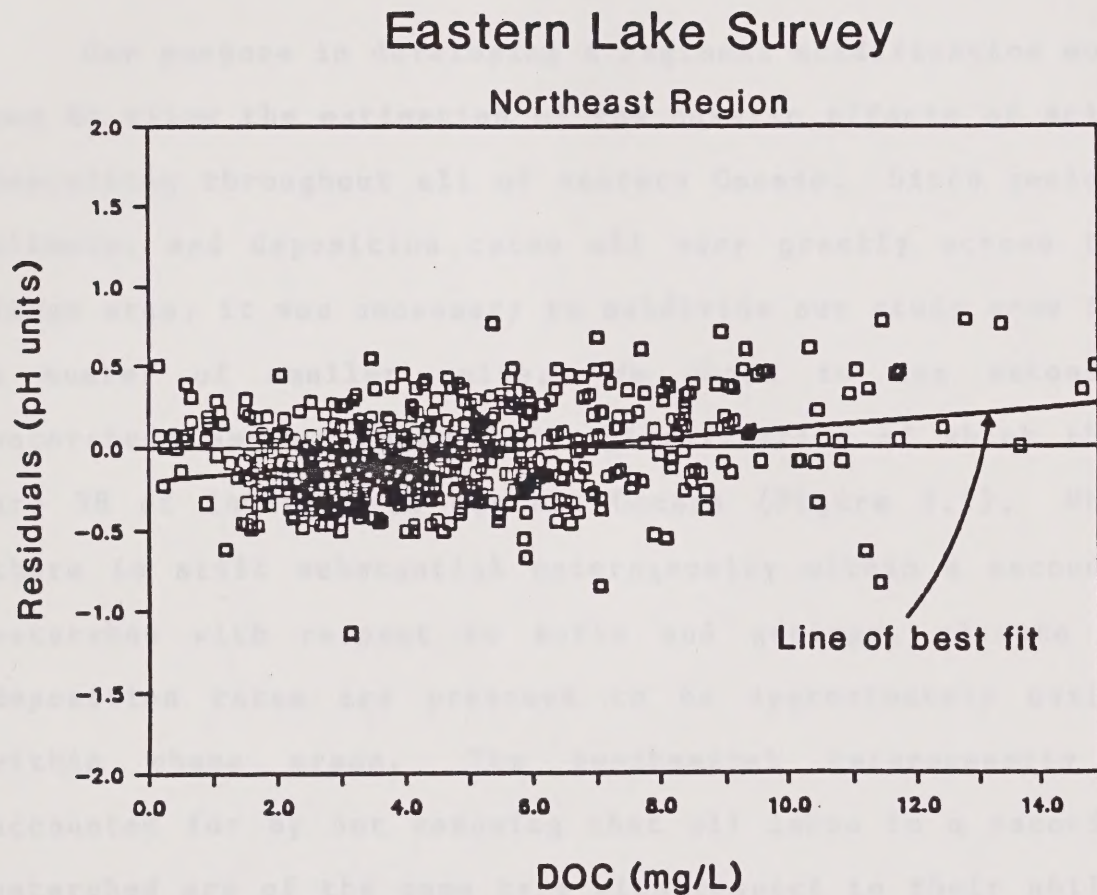


Figure 2.3: Residuals (observed - predicted) from the theoretical titration curve for data from the Eastern Lake Survey, Northeast Region, plotted as a function of DOC.

- 1) Current lake water concentrations;
- 2) Current lake alkalinity concentrations;
- 3) Current lake pH concentrations;
- 4) Original lake alkalinity concentrations;
- 5) Lake area;
- 6) Watershed area;
- 7) Runoff; and
- 8) Reported future deposition.

III REGIONALIZATION

3.1 Introduction

Our purpose in developing a regional acidification model was to allow the estimation of the aquatic effects of acidic deposition throughout all of eastern Canada. Since geology, climate, and deposition rates all vary greatly across this large area, it was necessary to subdivide our study area into a number of smaller units. We chose to use secondary watersheds as our basis for regionalization of which there are 38 of interest in eastern Canada (Figure 3.1). While there is still substantial heterogeneity within a secondary watershed with respect to soils and geology, climate and deposition rates are presumed to be approximately uniform within these areas. The geochemical heterogeneity is accounted for by not assuming that all lakes in a secondary watershed are of the same type with respect to their ability to neutralize deposited acidity.

Equation (14) can be used to calculate the eventual alkalinity of a lake given estimates of the following parameters:

- 1) Current base cation concentrations;
- 2) Current lake sulphate concentrations;
- 3) Current lake chloride concentrations;
- 4) Original lake sulphate concentrations;
- 5) Lake area;
- 6) Watershed area;
- 7) Runoff; and
- 8) Expected future deposition.

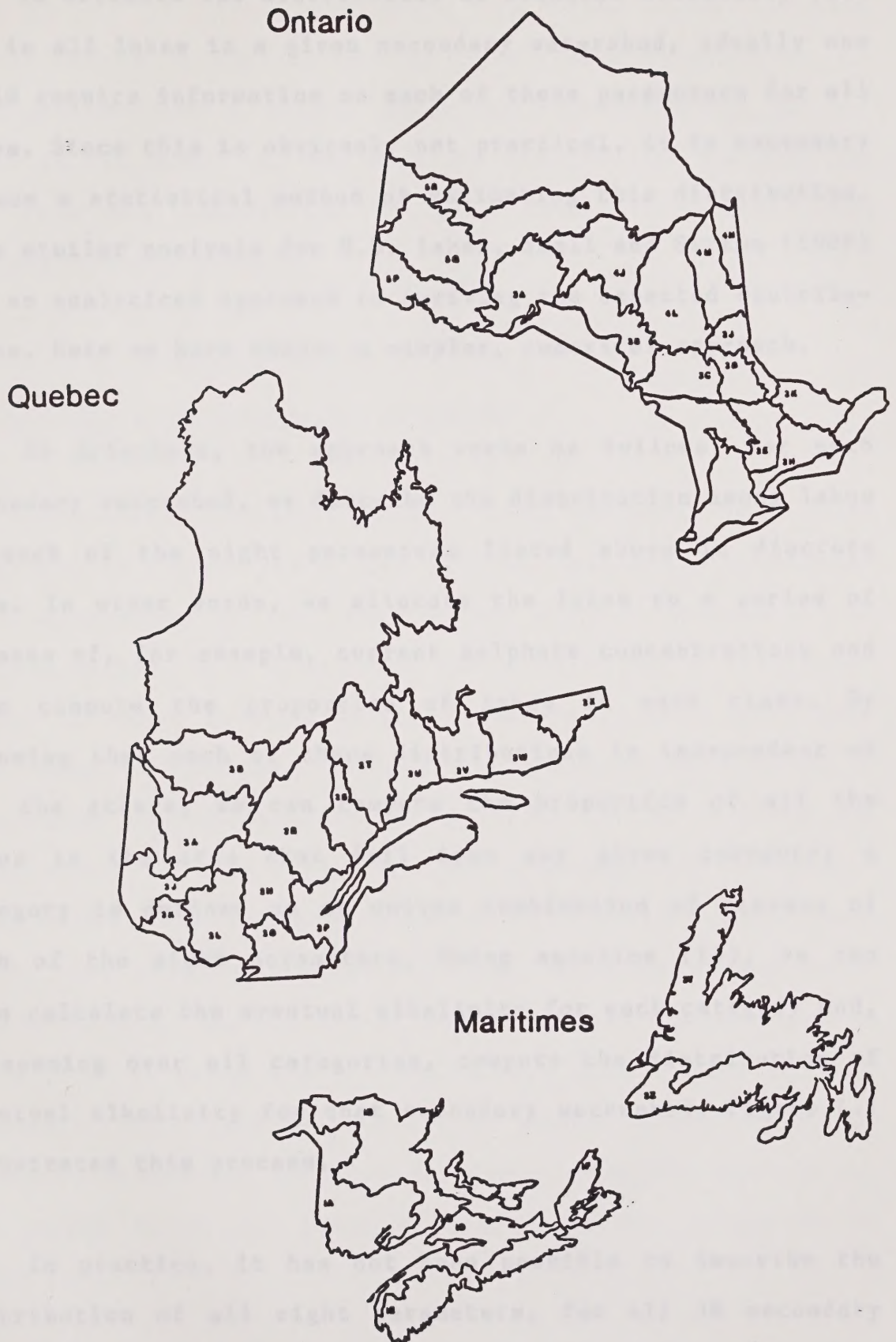


Figure 3.1: The 38 secondary watersheds used in the regional acidification model.

To estimate the distribution of eventual alkalinity (and pH) in all lakes in a given secondary watershed, ideally one would require information on each of these parameters for all lakes. Since this is obviously not practical, it is necessary to use a statistical method of estimating this distribution. In a similar analysis for U.S. lakes, Small and Sutton (1986) use an analytical approach to deriving the expected distributions. Here we have chosen a simpler, numerical approach.

In principle, the approach works as follows. For each secondary watershed, we describe the distribution among lakes of each of the eight parameters listed above in discrete form. In other words, we allocate the lakes to a series of classes of, for example, current sulphate concentrations and then compute the proportion of lakes in each class. By assuming that each of these distributions is independent of all the others, we can compute the proportion of all the lakes in the area that fall into any given category; a category is defined as a unique combination of classes of each of the eight parameters. Using equation (14), we can then calculate the eventual alkalinity for each category and, by summing over all categories, compute the distribution of eventual alkalinity for that secondary watershed. Figure 1.1 illustrates this process.

In practice, it has not been possible to describe the distribution of all eight parameters, for all 38 secondary watersheds of interest in eastern Canada. Some watersheds lack sufficient data to characterize the distributions of

some or all of these parameters. In these cases, we have either chosen to substitute data from a nearby watershed, or have argued that a single value is representative of all lakes in the area. In the sections that follow, we describe the data and assumptions we have used to complete the regionalization process.

3.2 Current Base Cations and Sulphate

Throughout eastern Canada, lake surveys have been conducted in recent years that provide relatively comprehensive information on the cationic and anionic composition of surface waters. With relatively few exceptions, a sufficient number of lakes in each of the 38 secondary watersheds have been sampled for base cations and sulphate to provide a reasonable characterization of the distribution of these two constituents in that watershed. Our criterion for an acceptable sample size was a minimum of 30 lakes for which both total base cations ($\text{Ca} + \text{Mg} + \text{Na} + \text{K}$) and sulphate measurements were available. The sources of these data are acknowledged in Table 3.1. In cases where a sufficient sample size was not available, we either substituted or lumped data from nearby secondary watersheds (Table 3.2). Means, standard deviations, and sample sizes for these distributions are presented in Table 3.3.

It should be noted that the survey data used to describe the distributions of these constituents were not derived from

Table 3.1: Sources of cation and sulphate data used as input to the regional model.

Province	Sources of Information
Ontario	Ontario Sensitivity Database (D. Wales, OMNR, pers. comm.)
Quebec	Naquadat Database (A. Fraser, DOE, pers. comm.)
Nova Scotia/ New Brunswick	National Inventory Survey (Kelso et al. 1986)
Newfoundland	Newfoundland Lake Survey Data (D. Scruton, DFO, St. John's, Nfld.)

Table 3.2: Secondary watershed substitutions required for Ontario, Quebec, and the Maritime provinces. In Quebec, adequate sample sizes were, in several cases, achieved by lumping data from adjacent watersheds rather than by substitution.

Watershed	Lake and Watershed Area	Current Base Cations and Sulphate
Ontario		
4G		4J
4M	4N	4L
4N		4L
5R		5Q
Quebec		
2J	2K	2J+2K
2K		2J+2K
2N	2O	
2P	2O	
2S	2U	2S+2T+2U
2T	2U	2S+2T+2U
2U		2S+2T+2U
2V	2U	2V+2W+2X
2W	2U	2V+2W+2X
2X	2U	2V+2W+2X
3A	2R	2R
3B	2R	2R
Maritimes		
1F		1D
2Y	2Z	

Table 3.3: Means, standard deviations, and sample sizes by watershed for total cation* and sulphate data used to calculate original alkalinity distributions.

Watershed	Cations		Sulphate		Sample Size
	Mean	Standard Deviation	Mean	Standard Deviation	
Ontario					
2a	655	496	92	29	63
2b	674	560	122	50	221
2c	304	159	217	60	122
2d	321	151	232	67	108
2e	285	294	153	35	538
2h	622	626	178	64	108
2j	418	485	170	35	141
2k	302	138	156	29	425
4g	2180	890	70	47	172
4j	2180	890	70	47	172
4l	1235	729	103	45	223
4m	1235	729	103	45	223
4n	1235	729	103	45	223
5p	392	257	73	20	246
5q	457	288	70	20	46
5r	457	288	70	20	46
Quebec					
2j	350	193	179	58	41
2k	350	193	179	58	41
2l	436	399	153	39	166
2n	166	46	90	30	40
2o	876	1091	244	211	33
2p	279	506	110	138	50
2r	185	91	65	22	72
2s	132	75	48	17	79
2t	132	75	48	17	79
2u	132	75	48	17	79
2v	93	28	33	12	42
2w	93	28	33	12	42
2x	93	28	33	12	42
3a	185	91	65	22	72
3b	185	91	65	22	72
Maritimes					
1a	163	145	83	17	69
1b	163	145	83	17	69
1d	104	75	77	12	41
1e	56	21	80	13	34
1f	104	75	77	12	41
2y	203	348	50	32	255
2z	87	32	46	10	32

* Total cations less chloride for maritime watersheds (1a-f, 2y, 2z)

random or statistically representative samples of the populations of lakes in a particular area. With the exception of the Nova Scotia data, however, we have no a priori reasons for assuming that our use of these data will give us a biased picture of the sensitivity of the population of lakes in a region, or of their response to emission control scenarios. In the case of Nova Scotia, we have taken steps to correct for oversampling of sensitive lakes in the region. The method of correction is described in a later section (3.8).

3.3 Current Lake Chloride Concentrations

There were substantial discrepancies among regions in the availability of chloride data. In non-Maritime regions, this constituent is typically less variable among lakes than the other ions of interest. Therefore we have chosen to assume a single, typical value for this parameter for all lakes in Ontario and Quebec, based on mean concentrations calculated from lakes sampled in the National Inventory Survey (Kelso et al. 1986). Values of 20 and 13 $\mu\text{eq L}^{-1}$ were used for Ontario and Quebec, respectively. For the Quebec watersheds north of the Gulf of St. Lawrence (2v,w,x) this may produce underestimates of chloride concentrations.

In the Maritime provinces, sea-spray inputs are substantial and variable among lakes; fortunately there is sufficient chloride data available in these areas to correct the total base cation data for chloride. Therefore, in these

regions we used distributions of total base cations less actual chloride, instead of simply subtracting a constant value for chloride from each lake.

Lakes receiving substantial road salt inputs will also have much higher than background chloride values. These lakes have been ignored in our analysis, as they comprise a very small fraction of the total sample of lakes in a region.

3.4 Original Lake Sulphate Concentrations

Since quality assured survey data is only available for very recent years, it is not possible to derive original sulphate distributions from surveys, except in remote areas where acidic sulphate deposition is very low. One method of estimating $[\text{SO}_4]_0$ is to apply estimates derived from these remote areas to areas receiving acid sulphate inputs. This method was used in our earlier analysis (Jones et al. 1984). For Quebec and the Maritimes, we used a value of $20 \mu\text{eq L}^{-1}$, based on estimates from lakes sampled in Labrador. In Ontario, estimates from northern Ontario lakes sampled in the National Inventory Survey suggested a much higher value ($100 \mu\text{eq L}^{-1}$) to be more representative. This value is now thought to be unreasonably high, however.

An alternative approach is based on the assumption that watershed sources of non-acidic sulphate are negligible, and therefore that estimates of non-acidic sulphate deposition

can be used to estimate $[SO_4]_0$. We used base cation deposition data from CAPMoN (Canadian Air Pollutant Monitoring Network) sites to estimate the amount of non-acidic sulphate deposition occurring in each secondary watershed (see section 3.7 below), and assumed that non-acidic sulphate deposition has not changed from historical levels. Original sulphate is then calculated from:

$$(15) \quad [SO_4]_0 = \frac{D_{\text{non-acidic}}}{R}$$

Estimates of $[SO_4]_0$ for each secondary watershed are presented in Table 3.4.

3.5 Lake and Watershed Areas

Analyses of the distributions of lake and watershed areas have been conducted for several watershed units throughout eastern Canada (watershed units are catchments comprising approximately 100-500 lakes in a network). Since equation (14) only requires knowledge of the ratio (r) of watershed area to lake area, we used these data to calculate distributions of $r/(r+1)$ for each watershed unit.

In Ontario the coverage is especially complete, with at least one watershed unit sampled in all but one of the secondary watersheds included in this analysis. In the Maritime provinces all but two secondary watersheds have been sampled, while in Quebec the coverage is much less extensive (4/14). As with cations and sulphate, we substituted data from adjacent watersheds when necessary (Table 3.2). The mean values of $r/(r+1)$ for each secondary watershed are presented in Table 3.4.

3.6 Runoff

Distributions of runoff values for each secondary watershed were derived from a visual interpretation of runoff isopleths on maps presented in the hydrological atlas of Canada. These maps are generated from long term hydrological data collected by the Water Survey of Canada. The data are therefore representative of the average runoff conditions experienced in a region over the long term. Since the model uses deposition data from 1980 (see section 3.7), it is worth examining the deviation of runoff values in 1980 from these long term averages (Table 3.5). The comparison indicates that differences between the 1980 values and the long term average values are relatively minor. Therefore we have chosen to use the long term average data to describe runoff distributions (Table 3.4).

Table 3.4: Non-acidic SO₄ deposition, runoff means, estimated [SO₄]₀, and mean values for r/(r+1) for each secondary watershed.

Watershed	Non-acidic SO ₄ Deposition (kg/ha/yr)	Runoff Means (m/yr)	Estimated [SO ₄] ₀ (µeq/L)	r/(r+1) Means
Ontario				
2a	9.98	0.33	30.72	.9187
2b	12.23	0.41	29.83	.9170
2c	13.92	0.36	38.87	.8874
2d	11.73	0.35	33.52	.9254
2e	15.54	0.42	36.99	.9127
2h	16.41	0.28	58.61	.9420
2j	10.30	0.35	29.42	.9167
2k	13.04	0.25	52.17	.9270
4g	7.99	0.35	22.82	.9228
4j	8.92	0.35	25.49	.8993
4l	9.92	0.35	28.35	.8711
4m	7.68	0.35	21.93	.8952
4n	6.86	0.45	15.25	.8952
5p	10.48	0.25	41.93	.8819
5q	8.11	0.25	32.45	.9171
5r	6.18	0.15	41.18	.8664
Quebec				
2j	9.55	0.43	22.20	.9341
2k	10.92	0.35	31.20	.9341
2l	9.48	0.44	21.56	.9341
2n	8.30	0.51	16.27	.9259
2o	9.30	0.58	16.03	.9259
2p	7.74	0.67	11.55	.9259
2r	6.55	0.65	10.08	.9271
2s	7.43	0.65	11.42	.9247
2t	5.55	0.69	8.05	.9247
2u	6.36	0.75	8.49	.9247
2v	6.49	0.83	7.82	.9247
2w	6.43	0.83	7.74	.9247
2x	5.87	0.73	8.04	.9247
3a	6.68	0.54	12.36	.9271
3b	5.18	0.55	9.50	.9271
Maritimes				
1a	9.80	0.63	15.55	.9100
1b	9.24	0.81	11.47	.9098
1d	9.67	0.81	12.01	.9098
1e	10.80	1.00	10.80	.8937
1f	12.17	1.01	12.06	.9163
2y	14.41	0.80	18.02	.9135
2z	9.98	1.01	9.89	.9135

Table 3.5: Comparison of runoff data from 1980 with the long term mean runoff for 48 gauging stations in eastern Canada. Data is from the Historical Streamflow summary reports published by Environment Canada.

Province	Number of Stations	Number of Secondary Watersheds Included	1980 Mean/Long-Term Mean
Ontario	15	11	0.967
Quebec	15	12	1.000
New Brunswick	6	2	0.927
Nova Scotia	6	3	0.945
Newfoundland	6	2	0.939

3.7 Deposition

In an earlier version of the model (Jones et al. 1984), deposition distributions were derived from an analysis of CANSAP data for 1981 for total wet deposition of sulphate. Actual observations were widespread in space and there was some concern that the distributions were a poor representation of actual sulphate deposition in a given area. In addition, dry deposition was simply estimated to be 25% of the total wet deposition in each region. Recently, new and more complete data for 1980 (P. Summers, M. Olson, A. Sirois, pers. comm.) has become available for 35 of the 38 secondary watersheds. The exceptions are Cape Breton Island and the two watersheds in Newfoundland (the method used to determine values for these areas is explained below).

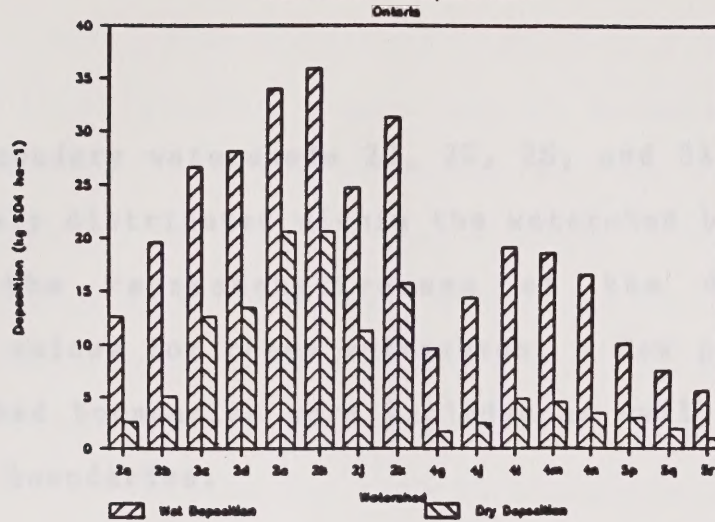
Estimates of annual total wet and dry deposition of sulphur ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$) for 1980 were provided by AES staff. Wet deposition values were supplied on a half-degree by half-degree grid of latitude and longitude, and were derived from CAPMoN data (annual summaries, 30-45 observation sites) by spatial interpolation using a procedure known as Kriging. Dry deposition estimates were more sparsely distributed (provided on a 100 km^2 grid of latitude and longitude) and derived by applying the Kriging method to model-derived estimates of air concentrations. Regionally varying deposition velocities (Voldmer et al. 1986) were then multiplied by these air concentration values, to arrive at dry deposition estimates.

In general, wet and dry sulphate deposition for each secondary watershed was calculated to be the mean value of all data points within the boundary of a watershed. Where data was either insufficient (i.e., too few data points within the boundaries) or non-existent (i.e., for watersheds 1F, 2Y and 2Z), alternative methods for determining wet and dry sulphate deposition values are discussed below. The actual values used for each secondary watershed are shown in Figure 3.2.

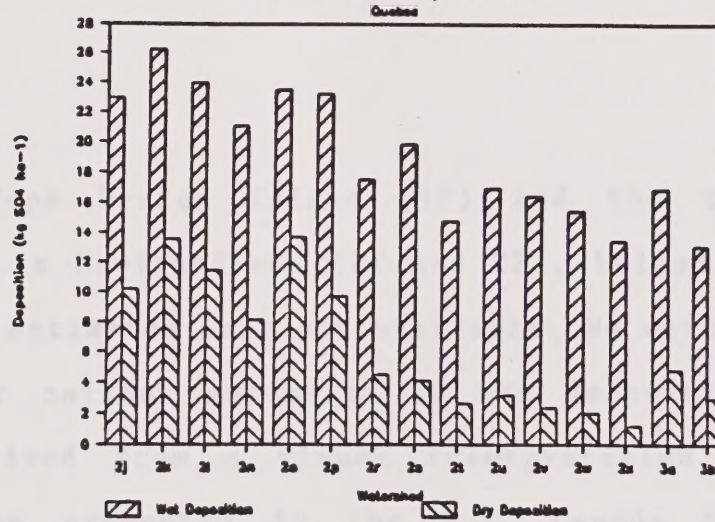
Ontario

In southern Ontario, only the northeastern part of watershed 2H contains soils and bedrock sensitive to acidic deposition. Two points to the north of the boundary of watershed 2H were thus assumed to better reflect the wet deposition in the sensitive areas of the watershed. For dry deposition, no estimates are available within the boundaries of watersheds 2D, 2H, and 4N. Therefore dry deposition estimates for the closest points around the perimeter of each watershed have been chosen to represent the watershed. For watershed 2K, where there are only two dry deposition points within the watershed boundary, we used all points within the watershed plus a point immediately to the north to provide a more reasonable estimate.

Estimated Deposition



Estimated Deposition



Estimated Deposition

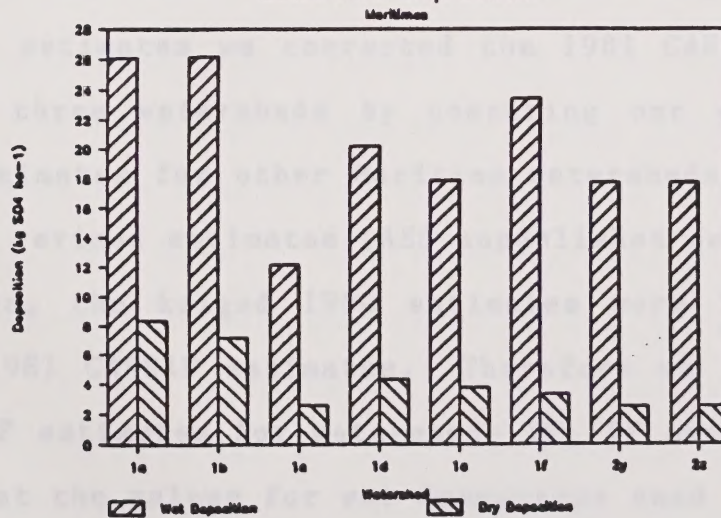


Figure 3.2: Estimated wet and dry sulphate deposition (kg/ha/yr) for secondary watersheds in Ontario, Quebec, and the Maritimes based on 1980 data.

Quebec

In secondary watersheds 2J, 2K, 2S, and 3A, data points were sparsely distributed within the watershed boundaries. To increase the representativeness of the dry sulphate deposition values for these watersheds, a few points outside the watershed boundaries were included as well as all points within the boundaries.

Maritimes

For Cape Breton Island (1F) and the two secondary watersheds in Newfoundland (2Y and 2Z), kriged wet sulphate deposition estimates were not available. We were thus obliged to use our earlier estimates of wet deposition for these areas, derived from a visual interpretation of the 1981 CANSAP maps presented in the U.S. Canada Memorandum of Intent. To maintain consistency across regions in our deposition estimates we corrected the 1981 CANSAP estimates for these three watersheds by comparing our earlier (1981 CANSAP) estimates for other Maritime watersheds (1A, 1B, 1D, 1E) to the revised estimates (AES unpublished data 1980). On the average, the kriged 1980 estimates were 12.99% higher than the 1981 CANSAP estimates. Therefore we increased the 1981 CANSAP estimates for watersheds 1F, 2Y and 2Z by 12.99% to arrive at the values for wet deposition used in our model. New dry sulphate deposition distributions for these relatively remote areas were estimated using data from Sirois

and Barrie (1987). They calculated, on a four year average, that 14% of total sulphate deposition at Montmorency, Quebec can be attributed to dry deposition. Because air masses in this region tend to move in an easterly direction, Cape Breton Island and Newfoundland would not be expected to receive higher inputs from dry deposition (relative to wet deposition) than Montmorency. Consequently, 14% of the total wet deposition calculated for each of these areas was used as a (maximum) estimate for dry deposition.

The only dry sulphate deposition value ($5.78 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ S) available for the two secondary watersheds in Nova Scotia appeared to be unreasonably high in comparison to New Brunswick values. Sirois and Barrie (1987) estimated that 21% of total sulphate deposition at Kejimikujik, Nova Scotia is due to dry deposition. Therefore, 21% of the wet sulphate deposition for watersheds 1D and 1E was used to derive estimates for dry deposition.

Non-acidic deposition values were also estimated for each of the 38 secondary watersheds (Table 3.4) using 1985 data from 13 CAPMoN stations inside the area of concern (P. Summers, AES, pers. comm.). For each station, the non-acidic fraction of deposition was calculated as the ratio of [Ca+Mg] to sulphate in wet deposition. This calculation assumes that any and all [Ca+Mg] in precipitation is derived from non-acidic sulphate salts. As well, nitrate and ammonium ions are not accounted for and are therefore implicitly assumed not to have any acidifying (or neutralizing) effect.

The non-acidic fractions for each CAPMoN station are, in turn, used to estimate non-acidic fractions for the surrounding secondary watersheds. Finally, the actual non-acidic sulfate deposition values for each secondary watershed were obtained by multiplying these fractions by the estimated wet deposition values.

3.8 Overall Resources at Risk

The preceding sections describe the information required to estimate the proportion of lakes in a region (i.e., a secondary watershed) whose eventual alkalinity or pH lies within (or below) a given range. To estimate the actual numbers or area of lakes affected, one also needs to know the size of the overall resource. In our analysis we have used the counts and measures data discussed in section 3.5 as our basis for estimating overall resources at risk.

The counts and measures data provide information on the total numbers and area of lakes within each of the watershed units sampled. As before, we assume that these samples provide a representative estimate of the number and area of lakes per unit area of watershed, for each secondary watershed the sample is used to represent. Together with estimates of the overall size of each secondary watershed, these data can be used to estimate the numbers or area of lakes in that watershed.

Secondary watershed areas and estimates of the number and area of lakes in each watershed are presented in Table 3.6. Where necessary, we have made the same watershed unit substitutions as listed in Table 3.2. In Nova Scotia, the data from which the cation and sulphate distributions were derived is biased towards sensitive lakes (K. Minns, pers. comm.). To account for this bias, and thus avoid overestimating the magnitude of resources at risk in Nova Scotia, we have corrected our estimates of the overall resource size to include only those lakes found in areas with granitic bedrock (Table 3.7).

25	3703	7233.50	42703.24
26	18122	2477.29	37989.87
27	14316	2333.29	20670.23
28	2331	2317.72	13143.58
29	4346	2362.87	21703.52
30	3135	1775.43	39672.18
31	5110	1345.82	24778.74
32	6045	1773.25	23131.13
40	11901	3143.33	42783.47
41	9244	2747.31	50982.78
42	11743	2403.18	42048.43
43	4387	1902.24	51142.71
44	3336	743.83	15571.15
50	11903	3367.53	41758.34
51	11132	3440.97	52376.37
52	4700	1040.38	19818.09
Total	137413	89127.74	557045.23
Quebec			
27	12809	1274.17	10627.80
28	6893	2743.75	3470.17
29	17002	2814.25	19238.32
29	12038	2452.52	14386.83

Table 3.6: Total numbers and area of lakes and total land area in secondary watersheds in Ontario, Quebec, New Brunswick, and Newfoundland.

Watershed	Total Number of Lakes	Total Area of Lakes (km ²)	Secondary Watershed Area (km ²)
Ontario			
2A	9755	7255.50	42703.26
2B	18222	2675.29	37984.67
2C	14510	3333.89	30670.85
2D	5331	2317.98	18166.58
2E	4346	2162.87	21705.52
2H	3295	1275.42	39872.10
2J	5140	1386.45	17458.79
2K	6048	1772.20	23121.10
4G	11981	8140.63	62285.41
4J	9298	2717.53	50960.79
4L	11241	2605.38	62049.49
4M	4387	1902.29	31142.71
4N	3336	743.83	15571.35
5P	12903	9367.66	41759.54
5Q	11122	9449.97	52376.37
5R	6500	3040.30	19818.09
Total	137415	60147.19	567646.62
Quebec			
2J	12809	2256.17	10627.80
2K	6493	1143.75	5470.19
2L	17000	2994.55	15238.39
2N	12058	2452.52	14300.65

Table 3.6: Continued

Watershed	Total Number of Lakes	Total Area of Lakes (km ²)	Secondary Watershed Area (km ²)
2O	3232	657.32	11721.84
2P	4401	895.24	11721.84
2R	18982	6858.33	27663.54
2S	17543	2034.50	8361.58
2T	30000	3479.00	21177.46
2U	22059	2558.09	12034.42
2V	21128	2450.00	10158.93
2W	22557	2615.79	11878.13
2X	14084	1633.34	7423.83
3A	14138	5108.28	12190.71
3B	12974	4687.98	23443.68
Total	229458	41824.86	203412.99
New Brunswick			
1A	6946	4172.60	34394.88
1B	7961	5601.09	36774.40
Total	14907	9773.69	71169.28
Newfoundland			
2Y	128208	10101.99	62408.32
2Z	85586	6743.62	43047.68
Total	213794	16845.61	105436.00

Table 3.7: Total number and area of lakes, number and area of lakes on granite or metamorphic bedrock, and total land area in Nova Scotia.

Watershed	Total Number of Lakes	Total Area of Lakes (km ²)	Total # Lakes on Granite	Total Area of Lakes (km ²) on Granite	Secondary Watershed Area (km ²)
1D	1254	398.98	678.78	278.36	19252.48
1E	4322	1593.11	3896.18	1516.34	23038.08
1F	1098	262.86	637.76	119.76	9085.44
	6674	2254.95	5212.72	1914.46	51376.00

IV APPLICATION OF THE REGIONAL MODEL

4.1 Introduction

In preceding sections we described the site model and the data and assumptions used to apply the model on a regional scale. In this section we present the results of applying the regional model, first to individual secondary watersheds, and subsequently to all of eastern Canada. The regional applications are intended to address four questions:

- 1) How sensitive are the model's predictions to our assumptions about key parameter values?
- 2) In a regional scale, how much change does the model predict has already occurred in lake pH and alkalinity, and how much further change is expected, given the current (1980) acidic sulphate deposition rates presented in Figure 3.2?
- 3) What will be the difference in eventual pH and alkalinity distributions, for all regions of eastern Canada, given three alternative scenarios of sulphur emission controls? and
- 4) How much lime would be required to prevent all lakes in a region from exceeding minimum alkalinity targets, given the current (1980) acidic sulphate deposition rates?

4.2 Sensitivity Analysis

The site model contains two parameters whose values can only be inferred from data, rather than directly measured. These are original sulphate and F_w . The accuracy of our estimates of these parameters is thus difficult to judge, so

it is useful to examine the sensitivity of the model's predictions to variations in their value over a range that is physically realistic. In this analysis we assume that the relationship between F_w and original alkalinity (Equation (4)) is true and that our uncertainty lies exclusively with the value of the parameter b .

The sensitivity of the site model to these parameters can be shown by differentiating equation (14) with respect to $[SO_4]_0$ and F_w :

$$(16) \quad \frac{\delta Alk_{\infty}}{\delta [SO_4]_t} = -1 + F_w \left[\frac{r}{r+1} \right]$$

$$(17) \quad \frac{\delta Alk_{\infty}}{\delta F_w} = -\frac{r}{r+1} \left[\frac{D_{\infty}}{R} \left(1 - \frac{S_s}{R(r+1)+S_s} \right) - \left([SO_4]_t - [SO_4]_0 \right) \right]$$

From equation (16) it can be seen that the predicted eventual alkalinity becomes increasingly sensitive to the value of original sulphate, as F_w approaches zero. Since the value of F_w in turn depends on the lake's original alkalinity, the model is more sensitive to the value of original sulphate in acid sensitive lakes. For small values of F_w , the eventual alkalinity is nearly directly proportional to $[SO_4]_0$.

Although the site model's sensitivity to F_w is less obvious, equation (17) does illustrate one important prop-

erty. The actual sensitivity will depend on the closeness of the lake(s) for which the eventual alkalinity is being predicted to steady state with respect to acid sulphate deposition. The D_{∞}/R term of equation (17) determines the sulphate derived acidity not consumed within the lake while the $[SO_4]_t - [SO_4]_0$ term indicates the amount by which the lake's sulphate concentration has changed from its original state to the present. Their difference is a measure of how far the lake is from its eventual steady state, and is proportional to the model's sensitivity to F_w .

The combined sensitivity of the model to uncertainty in these two parameters is best illustrated by running the regional model while allowing both parameters to vary over a plausible range of values. Earlier investigations have indicated that plausible values of $[SO_4]_0$ range from approximately 10-100 $\mu\text{eq.L}^{-1}$ (Wright 1983; Jones et al. 1984, 1987) depending on the assumptions underlying its derivation. As noted earlier, F_w has been estimated to vary from 0 - 0.7 in lakes considered sensitive to acidification. It is unlikely that lakes with original alkalinities less than 200 $\mu\text{eq.L}^{-1}$ are insensitive to acidification; this suggests that a minimum plausible value for b would be 200. As an upper bound for this parameter we have chosen 1000. The latter value implies greater sensitivity for low alkalinity lakes ($F_w \ll 1$).

The sensitivity analysis was completed by running the regional model for Ontario watershed 2C, using the distribu-

tions and parameters listed above, but allowing $[SO_4]_0$ to vary from 10-100 $\mu\text{eq.L}^{-1}$ in increments of 10 and b to vary from 200-1000 $\mu\text{eq.L}^{-1}$ in increments of 100. We have plotted the predicted proportion of acid lakes (alkalinity less than zero) for each combination of $[SO_4]_0$ and b (Figure 4.1). It is readily apparent from this figure that the predicted proportion of acid lakes is far more sensitive to $[SO_4]_0$ than to b. For values of b greater than 500 $\mu\text{eq.L}^{-1}$, the predicted value is virtually unaffected by changes in this parameter. On the other hand, at all values of b, the model's sensitivity to $[SO_4]_0$ is considerable. This analysis suggests that a priority for future research and data analysis should be the acquisition of more accurate and defensible estimates of original sulphate.

The results of this sensitivity analysis must be interpreted with caution. While the large sensitivity of the model to variations in $[SO_4]_0$ is likely a general result, the sensitivity to F_w (b) may be much greater in regions where the lakes are, on average, further from steady state with respect to acidic sulphate deposition. As will be shown below, there are a number of secondary watersheds in eastern Canada where this would appear to be the case. In the regional application results presented below, we have used the original sulphate values presented in Table 3.4, and have assumed that $a=0$ and $b=200$, in calculating F_w from Alk_0 . We would recommend that the regional model runs be repeated at some later date with other values of these key parameters, to ascertain the influence of our uncertainty on the regional

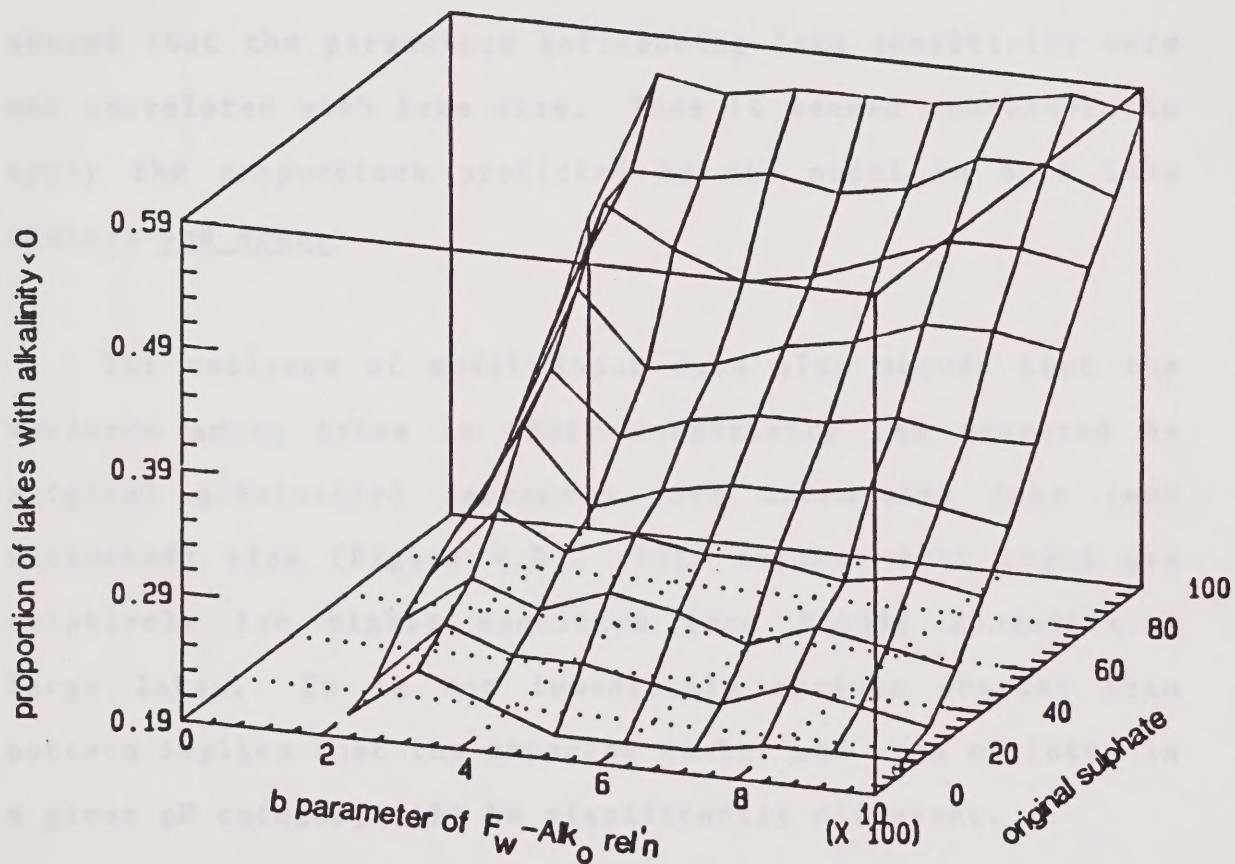


Figure 4.1: The predicted proportion of acid lakes (alk < 0) for different combinations of original sulphate and b.

scale predictions of damage and recovery.

When applying an earlier version of the regional model (Jones et al. 1984) our estimates of regional scale impacts were presented as the proportion of the total number of lakes in a region that will lie in a given eventual pH or alkalinity class. Analyses of the model input data, however, showed that the parameters influencing lake sensitivity were not correlated with lake size. Thus it seemed reasonable to apply the proportions predicted by the model to both lake numbers and area.

The analyses of model input data also showed that the variance among lakes in their sensitivity (as measured by original alkalinity) decreases with increasing lake (and watershed) size (Figure 4.2). This implies that there are relatively few highly sensitive (and highly insensitive) large lakes. It is not immediately obvious whether this pattern implies that the expected number and area of lakes in a given pH category will be significantly different.

It is possible to test this assumption by weighting the original alkalinity distribution used to predict eventual distributions according to the area of lakes in each category. The resulting eventual pH and alkalinity distributions can be compared to those resulting from the unweighted original alkalinity distributions. Figures 4.3 - 4.4 present the results of this test for two Ontario secondary watersheds. It is evident that the unweighted (numbers) and area

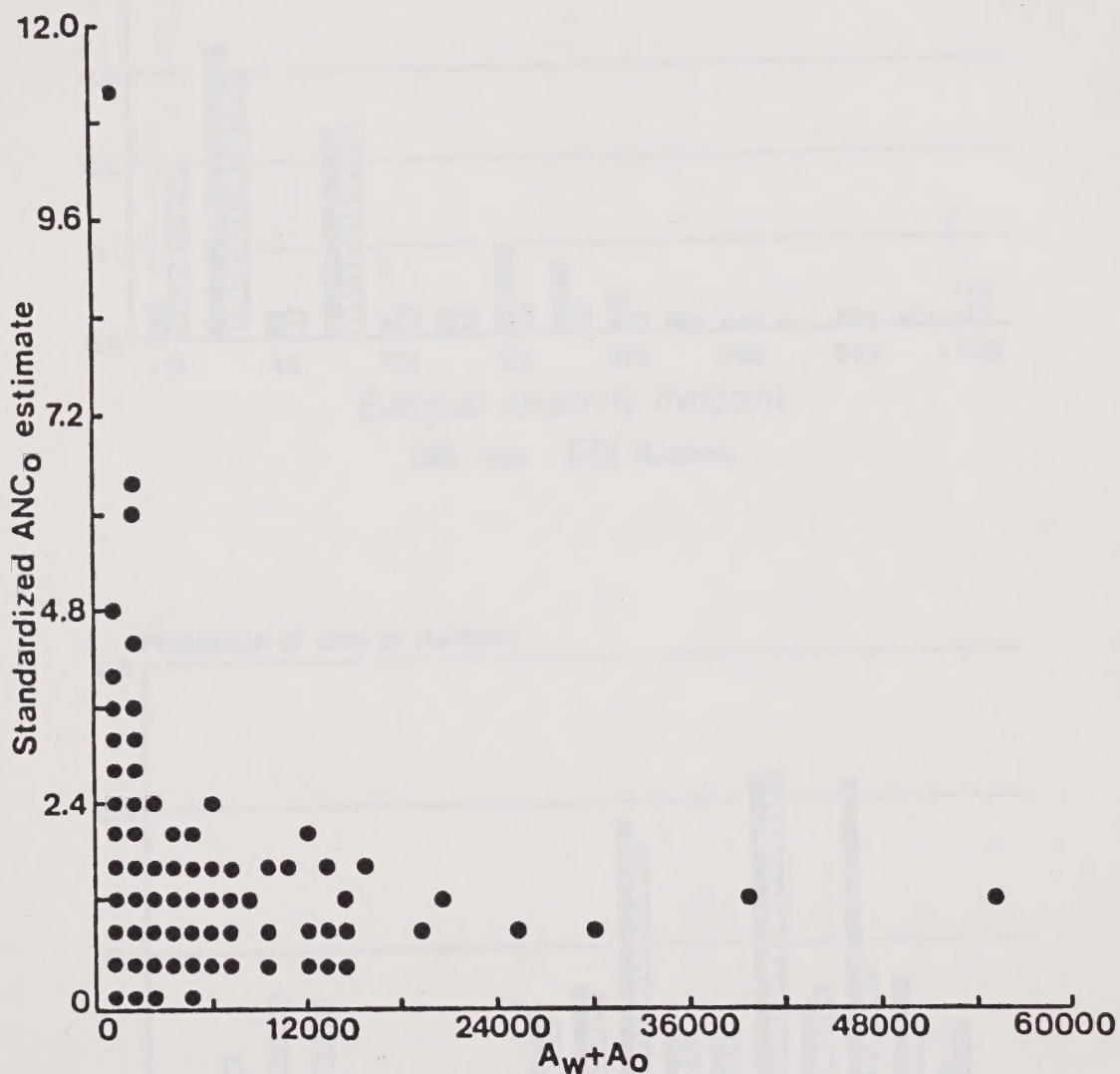


Figure 4.2: Standardized ANC₀ estimates related to total basin area for 807 NIS lakes. ANC₀ estimates were standardized by dividing the individual lake values by the mean for the region in which each was found. (from Jones et al. 1984)

Sensitivity Analysis Watershed 2C

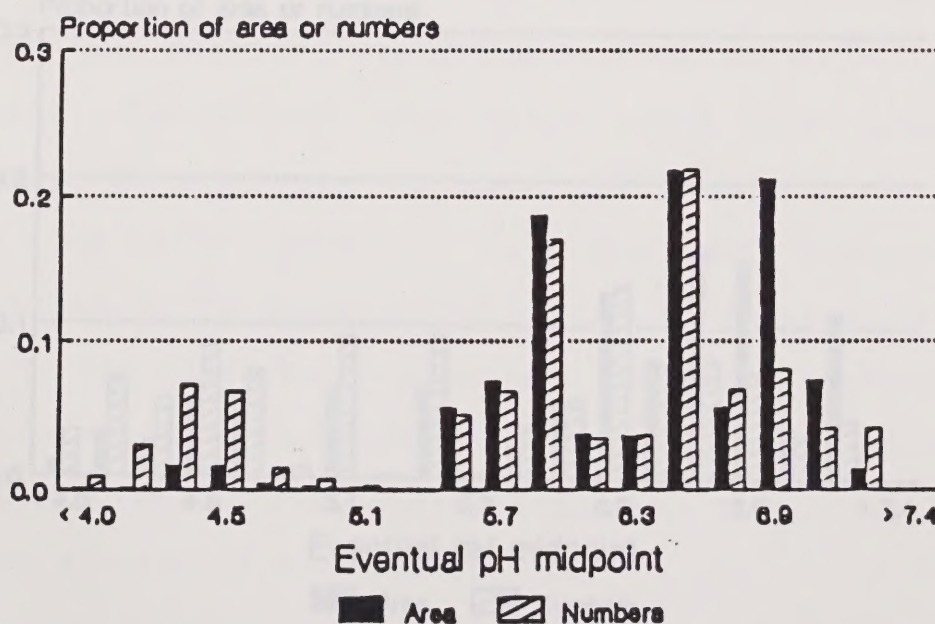
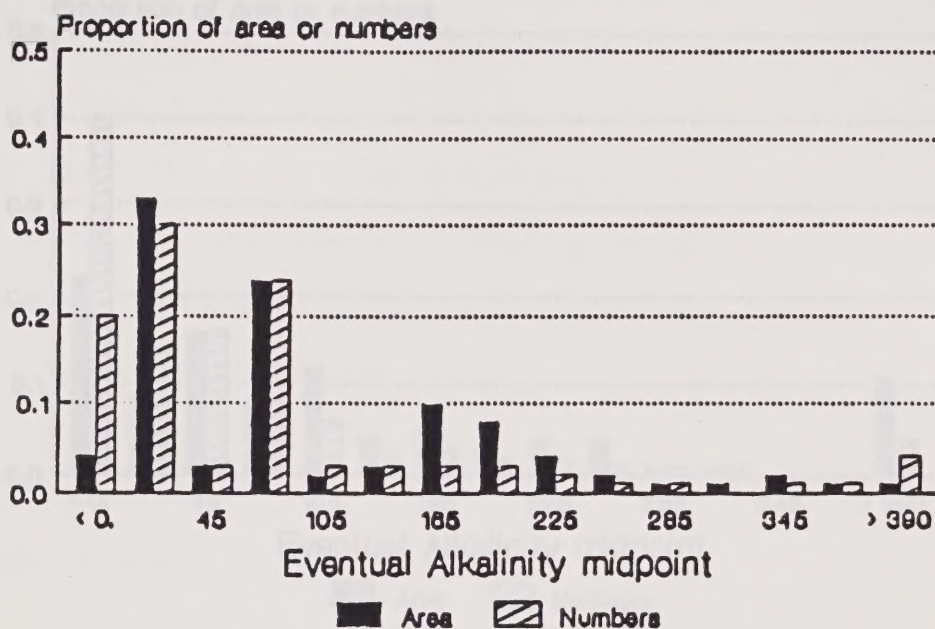


Figure 4.3: Predicted proportion of lakes in eventual alkalinity (upper panel) and pH (lower panel) categories for using numbers and area weighted original alkalinity distributions: Watershed 2C.

Sensitivity Analysis Watershed 2E

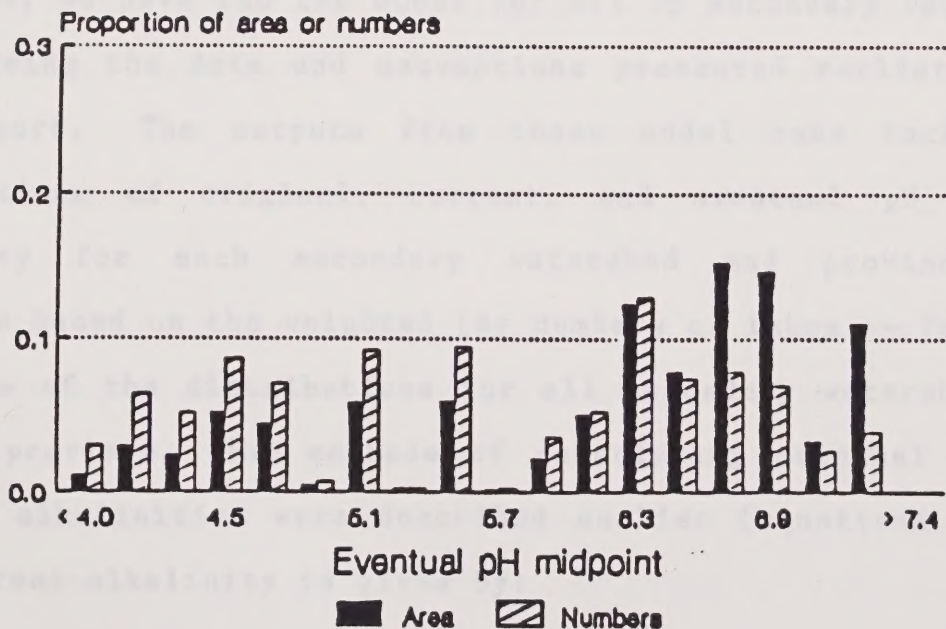
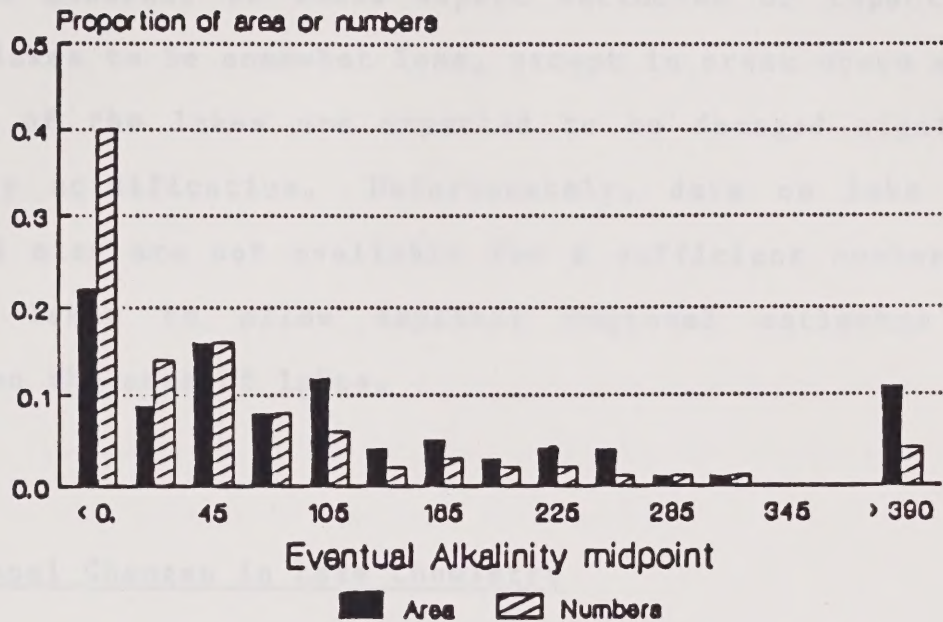


Figure 4.4: Predicted proportion of lakes in eventual alkalinity (upper panel) and pH (lower panel) categories for using numbers and area weighted original alkalinity distributions: Watershed 2E.

weighted (area) distributions are substantially different in both cases. These results have led us to conclude that our regional impact estimates only apply to numbers of lakes, not area. In general, we would expect estimates of impact on area of lakes to be somewhat less, except in areas where more than 50% of the lakes are expected to be damaged significantly by acidification. Unfortunately, data on lake and watershed size are not available for a sufficient number of surveyed lakes to allow explicit regional estimates of impacts on the area of lakes.

4.3 Regional Changes in Lake Chemistry

To examine the magnitude of chemical change predicted by the model, we have run the model for all 38 secondary watersheds, using the data and assumptions presented earlier in this report. The outputs from these model runs include distributions of original, current, and eventual pH and alkalinity for each secondary watershed and provincial summaries based on the weighted (by numbers of lakes -- Table 3.6) sums of the distributions for all secondary watersheds in that province. The methods of calculating original and eventual alkalinities were described earlier (equations 13, 14); current alkalinity is given by:

$$(18) \quad [\text{Alk}]_t = [\text{C}]_t - [\text{Cl}]_t - [\text{SO}_4]_t$$

which is identical to equation (11) except for the subscripts.

The predicted magnitude of chemical change can be seen by considering the median alkalinity and pH values, originally, currently, and eventually, for each secondary watershed (Table 4.1). It is evident from this table that considerable decreases in median alkalinity (and to a lesser extent, pH) are estimated to have occurred for virtually all regions where median original alkalinities are less than 200 $\mu\text{eq.L}^{-1}$. Furthermore, significant additional decreases are expected in the future in several watersheds.

The changes are most striking in south-central and northeastern Ontario (watersheds 2C, 2D, 2E, 2H, 2J, 2K). Predicted total (original to eventual) median alkalinity decreases range from 60-110 $\mu\text{eq.L}^{-1}$ for these watersheds (pH declines of 0.2-1.3 units). Clearly, changes of this magnitude are expected to result in significant biological damage.

The overall magnitude of changes in Ontario appears very small, due to large number of remote, high alkalinity lakes in the Ontario database (watersheds in regions 4 and 5). In contrast, substantial changes are expected on the provincial scale in Quebec. This is in part an artifact of the watersheds chosen for inclusion in the analysis, but also reflects the fact that Quebec has a relatively large area south of 52° N latitude containing soils and bedrock with a low potential to neutralize acidic inputs (Shilts et al. 1981).

Table 4.1: Original, current, and eventual median alkalinity and pH values.

Wshed	Median Alkalinity			Median pH		
	Original	1980-Base	Current	Original	1980-Base	Current
Total	100.3	62.2	73.4	6.6	6.4	6.5
Ontario	305.6	302.7	302.5	7.1	7.1	7.1
1/2A	382.5	382.5	375.0	7.2	7.2	7.2
1/2B	255.0	255.0	250.0	7.0	7.0	7.0
1/2C	115.0	26.8	33.2	6.7	6.0	6.2
1/2D	117.6	26.8	44.2	6.7	5.9	6.3
1/2E	109.7	0.0	53.1	6.7	5.4	6.4
1/2H	165.0	90.0	150.0	6.8	6.5	6.8
1/2J	147.8	87.8	103.3	6.8	6.6	6.7
1/2K	135.7	23.6	95.0	6.8	6.0	6.6
1/4G	404.7	404.7	404.7	7.3	7.3	7.3
1/4J	404.7	404.7	404.7	7.3	7.3	7.3
1/4L	402.6	402.6	402.6	7.3	7.3	7.3
1/4M	402.6	402.6	402.6	7.3	7.3	7.3
1/4N	402.6	402.6	402.6	7.3	7.3	7.3
1/5P	221.3	221.3	220.0	7.0	6.9	7.0
1/5Q	290.8	290.8	289.1	7.1	7.1	7.1
1/5R	290.8	290.8	289.1	7.1	7.1	7.1
Quebec	91.3	53.8	64.9	6.6	6.3	6.4
2/2J	137.7	93.0	83.3	6.8	6.5	6.6
2/2K	137.7	90.0	83.3	6.8	6.6	6.6
2/2L	175.0	144.5	150.0	6.9	6.8	6.8
2/2N	98.1	40.0	55.5	6.6	6.3	6.4
2/2O	168.5	138.5	144.0	6.9	6.7	6.8
2/2P	104.1	63.0	52.9	6.7	6.4	6.4
2/2R	111.4	81.4	84.3	6.7	6.5	6.6
2/2S	83.6	53.6	55.7	6.6	6.2	6.4
2/2T	84.0	54.0	55.7	6.6	6.4	6.4
2/2U	84.0	54.0	55.7	6.6	6.4	6.4
2/2V	60.0	30.0	47.6	6.4	6.2	6.3
2/2W	60.0	30.0	47.6	6.4	6.2	6.3
2/2X	60.0	30.0	47.6	6.4	6.2	6.3
2/3A	111.4	81.4	84.3	6.7	6.5	6.6
2/3B	111.4	81.4	84.3	6.7	6.5	6.6
Maritimes	78.4	47.8	55.1	6.5	6.3	6.4
3/1A	92.7	35.6	50.8	6.6	6.2	6.3
3/1B	92.7	62.7	50.8	6.6	6.4	6.3
3/1D	110.0	80.0	60.0	6.7	6.5	6.4
3/1E	30.0	< 0	< 0	6.1	5.4	4.3
3/1F	85.0	58.0	47.0	6.6	6.4	6.3
3/2Y	94.1	65.0	78.0	6.6	6.4	6.5
3/2Z	63.8	33.8	37.2	6.4	6.2	6.2

The most interesting element of the results for the Maritime provinces is the contrast between Nova Scotia and the other two provinces. As for sensitive watersheds in Ontario and Quebec, all the Maritime watersheds show pronounced declines in median alkalinities from original to current ($16-50 \mu\text{eq.L}^{-1}$). In New Brunswick and Newfoundland these declines are predicted to continue into the future. In Nova Scotia, however, the model predicts a recovery of the lakes in all three secondary watersheds, although in watershed 1E the median alkalinity remains below zero. Although there is apparently some evidence that deposition has decreased somewhat in the Maritimes in recent years (F.C. Elder, Environment Canada, personal communication), it is surprising that recovery is predicted in Nova Scotia but not New Brunswick.

The most plausible explanation for this result is that our estimates of original sulphate are low for Nova Scotia, relative to other provinces. This would be possible if marine salt contributions of sulphate are underestimated using the methods discussed in Section 3.4, since such errors would be expected to affect Nova Scotia more than any other province. The extreme sensitivity of the model to uncertainty in original sulphate implies that relatively minor

errors could have major effects. Underestimates of original sulphate would give rise to overestimates of original and eventual alkalinities but would not affect current alkalinity. Thus a higher value for $[SO_4]_0$ would result in lower original and eventual alkalinities, relative to current, and thereby reduce or even eliminate the trend toward recovery.

4.4 Effects of Emission Controls on Regional Chemistry

The results presented in the previous section indicated that in most regions with surface waters sensitive to acidification, considerable damage has already occurred or is expected given the 1980 deposition estimates. Since emission reduction strategies have been proposed, whose purpose is to minimize or even reverse this damage, it is important to evaluate how much benefit we might expect to derive from the implementation of such strategies. The regional model is ideally suited to addressing questions of this type.

Three emissions scenarios have been developed (Table 4.2) which, together with the 1980 scenario presented earlier, can be used to examine the predicted consequences of alternative emission control policies. The first involves reducing emissions in all source regions of eastern Canada by 42% from 1980 levels. The second allows for an equivalent reduction of all U.S. sources in addition to the Canadian

Table 4.2: Emission control scenarios and 1980 baseline emissions (KT SO₂) for regions of Canada and the United States.

Region No. ³ and Identifier	1980-Base ¹	Canada Only	Canada and US	Worse by 10%
10 NMN	699.13	520.00	520.00	769.00
11 SMN	38.87	30.00	30.00	42.80
12 NWO	29.77	10.00	10.00	32.80
13 NEO	215.94	129.50	129.50	237.50
14 SUD	1126.39	478.30	478.30	1239.00
15 SWO	779.93	390.20	390.20	857.90
16 SEO	41.95	22.00	22.00	46.10
17 SLV	437.81	260.00	260.00	481.60
18 NQU	524.51	275.00	275.00	577.00
19 GBY	122.67	65.00	65.00	134.90
20 NBK	215.00	185.00	185.00	236.50
21 NSP	225.00	209.00	209.00	247.50
22 NFL (4516)	59.00 (2619)	45.00	45.00	64.90
23 ASK	597.15	597.15	597.15	656.90
24 BCA	192.87	192.87	192.87	212.20
CANADA	5305.99	3409.02	3409.02	5836.60
50 OHO	2401.10	2401.10	1392.60	2641.20
51 ILL	1334.10	1334.10	773.80	1467.50
52 PENN	1834.50	1834.50	1064.00	2017.90
53 IND	1821.50	1821.50	1056.50	2003.70
54 KEN	1016.70	1016.70	589.70	1118.40
55 MCH	822.70	822.70	477.20	905.00
56 TENN	976.60	976.60	566.40	1074.30
57 MSU	1180.40	1180.40	684.60	1298.40
58 WVR	986.80	986.80	572.30	1085.50
59 NYK	856.70	856.70	496.90	942.40
60 ALA	688.30	688.30	399.20	757.10
61 WIO	876.40	876.40	508.30	964.00
62 MIN	236.20	236.20	137.00	259.80
63 VNC	873.90	873.90	506.90	961.30
64 FLD	993.30	993.30	576.10	1092.60
65 GSC	1057.50	1057.50	613.30	1163.30
66 MDJ	672.50	672.50	390.00	739.70
67 ALM	626.60	626.60	363.40	689.30
68 MCR	391.50	391.50	227.00	430.60
69 MAN	86.00	86.00	49.80	94.60
70 VNH	90.50	90.50	52.50	99.50
71 WNE	515.70	515.70	299.10	567.30
72 WSE	1832.60	1832.60	1062.90	2015.90
73 WNW	343.70	343.70	199.30	378.10
74 WSW	1506.70	1506.70	873.90	1657.40
U.S. ²	24022.50	24022.50	13932.68	26424.80

1. 1980-Base emissions proportioned as per MOI, Workgroup 3B.

2. As per MOI, Workgroup 3B. Alaska and Hawaii omitted.

3. For explanation of source region and identifier code see Ferguson and Machta (1982).

controls. The third represents a 10% increase in emissions "across the board", and is intended to simulate a worst-case scenario.

To apply these scenarios to the regional model, it is necessary to translate changes in emissions into changes in deposition. We have used the following procedure. First, deposition estimates were derived for nine Canadian receptor sites using a unit transfer matrix (after Olson et al. 1983). The transfer matrix contains 360 entries representing the predicted transport of sulphur emissions from forty emission regions throughout North America to nine Canadian receptor sites, using the AES-LRTAP model.

Next we determined the location (latitude/longitude) of the nine receptor sites and of the centroid of each of the 38 secondary watersheds of interest in eastern Canada. This allowed us to estimate the distance between each of the receptor sites and watershed centroids using the equation:

$$(19) d_{i,j} = .696(60(\text{long}_i - \text{long}_j))^2 + 1.151(60(\text{lat}_i - \text{lat}_j))^2$$

where i and j refer to the watershed and receptor site respectively, and the coefficients reflect the difference between a minute of longitude, a minute of latitude, a nautical mile, and a statute mile at fifty degrees latitude.

Finally, we estimated the expected deposition for each watershed using the equation (after Patterson et al. 1981):

$$(20) \quad D_i = \frac{\sum_j D_j (1/d_{i,j})^2}{\sum_{ij} (1/d_{i,j})^2}$$

The wet sulphate deposition values predicted for each secondary watershed using this method were consistently lower than the observed values, when the 1980 scenario was compared to the 1980 data (Figure 3.2). This is to be expected, since the model upon which the transfer matrix is based does not include sulphur from non-anthropogenic, or non-North American sources. The difference between predicted and observed values can be considered "non-controllable" sulphate deposition. Since the magnitude of this component should not be affected by emission controls, its value obtained from comparing the 1980 scenario to 1980 observations can be used directly to correct the predicted sulphate deposition for the other three scenarios. Thus, the deposition values used for each scenario in the regional model were calculated from the sum of the interpolated value from the transfer matrix output and the difference between the 1980 observed value and the 1980 predicted value. The predicted wet sulphate deposition values for each scenario and secondary watershed are presented in Figures 4.5-4.7. The 1980 predictions are referred to as the baseline scenario. Dry sulphate deposition (not

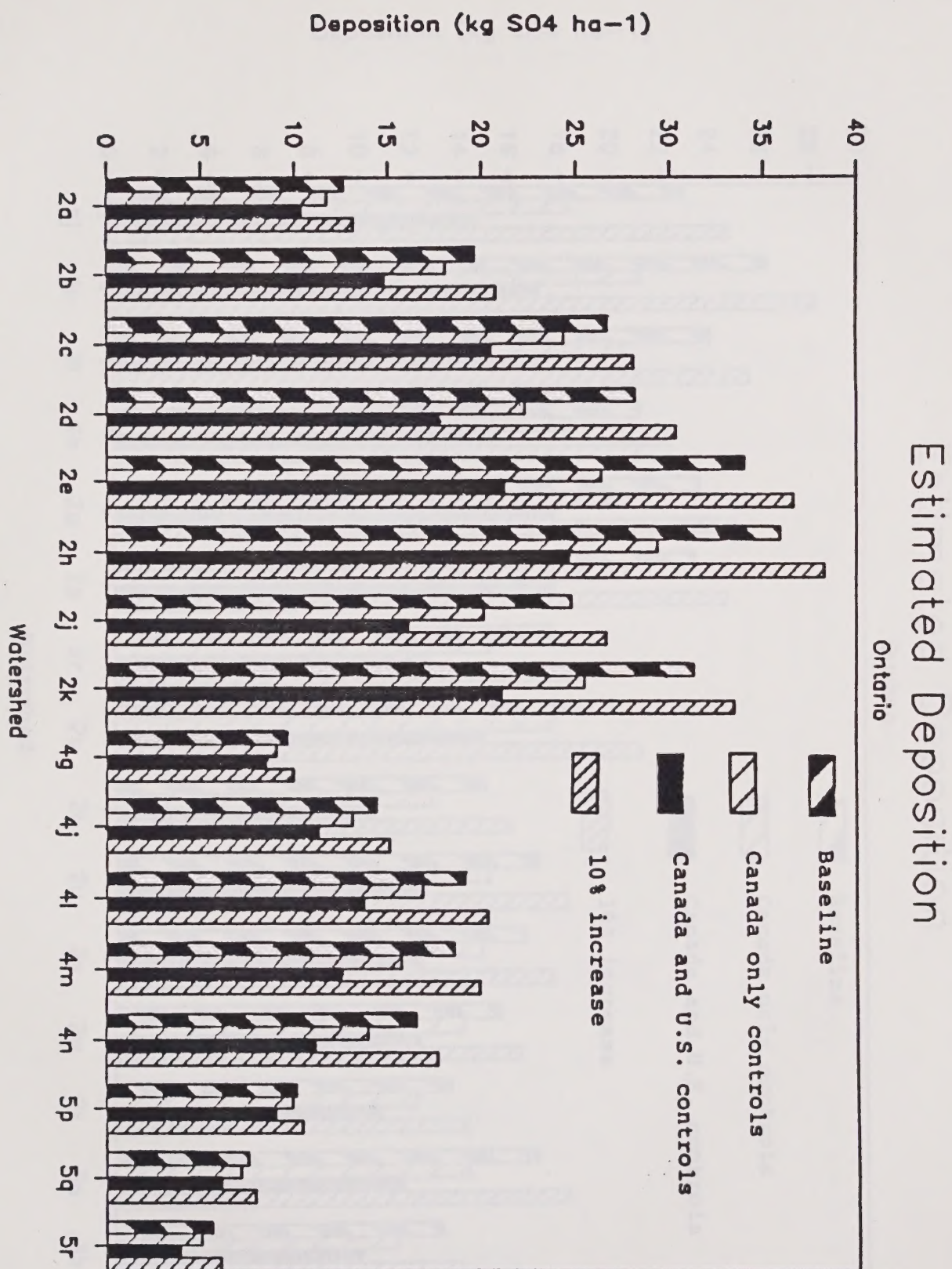


Figure 4.5: Predicted wet sulphate deposition values, by Ontario secondary watersheds, for each scenario.

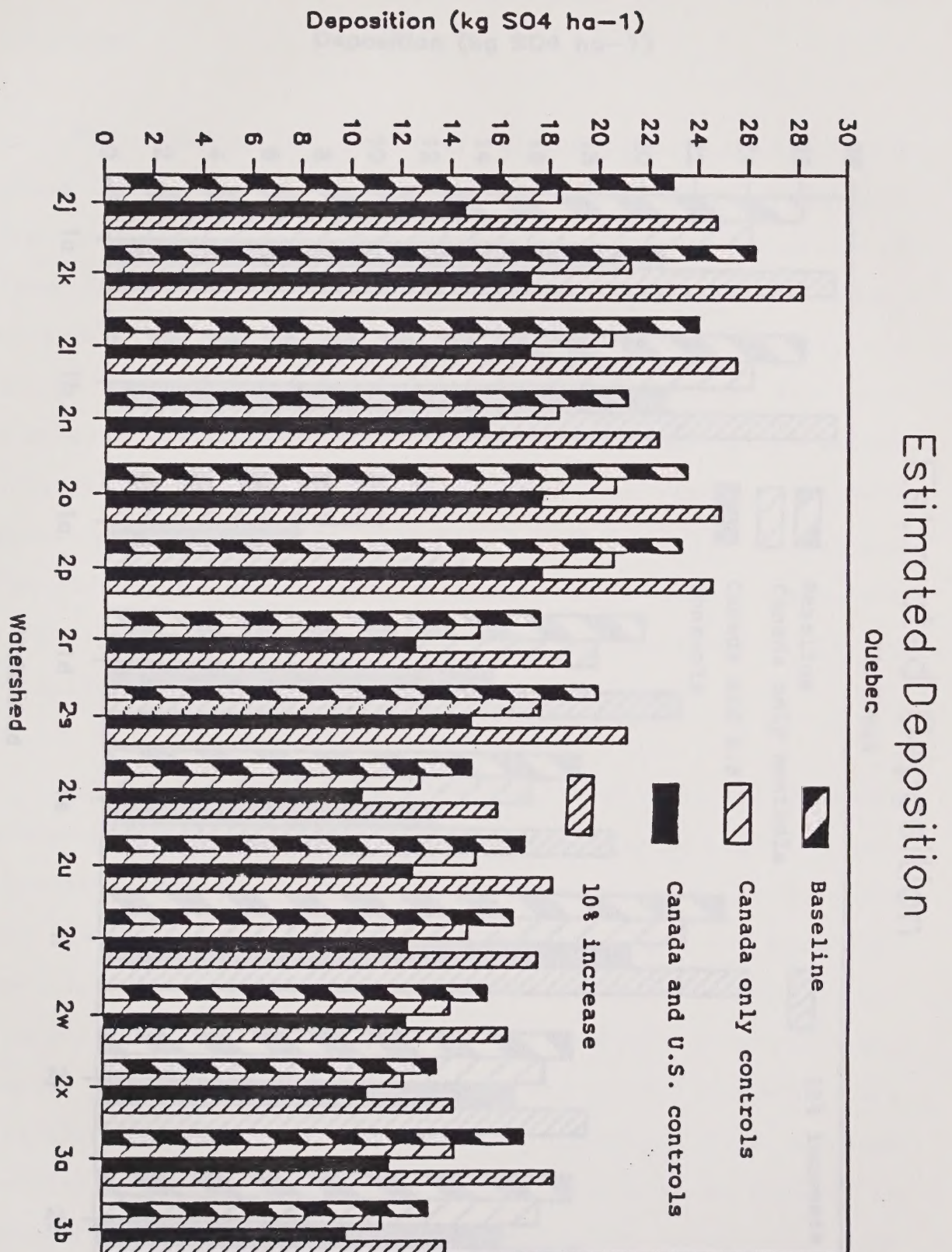


Figure 4.6: Predicted wet sulphate deposition values, by Quebec secondary watersheds, for each scenario.

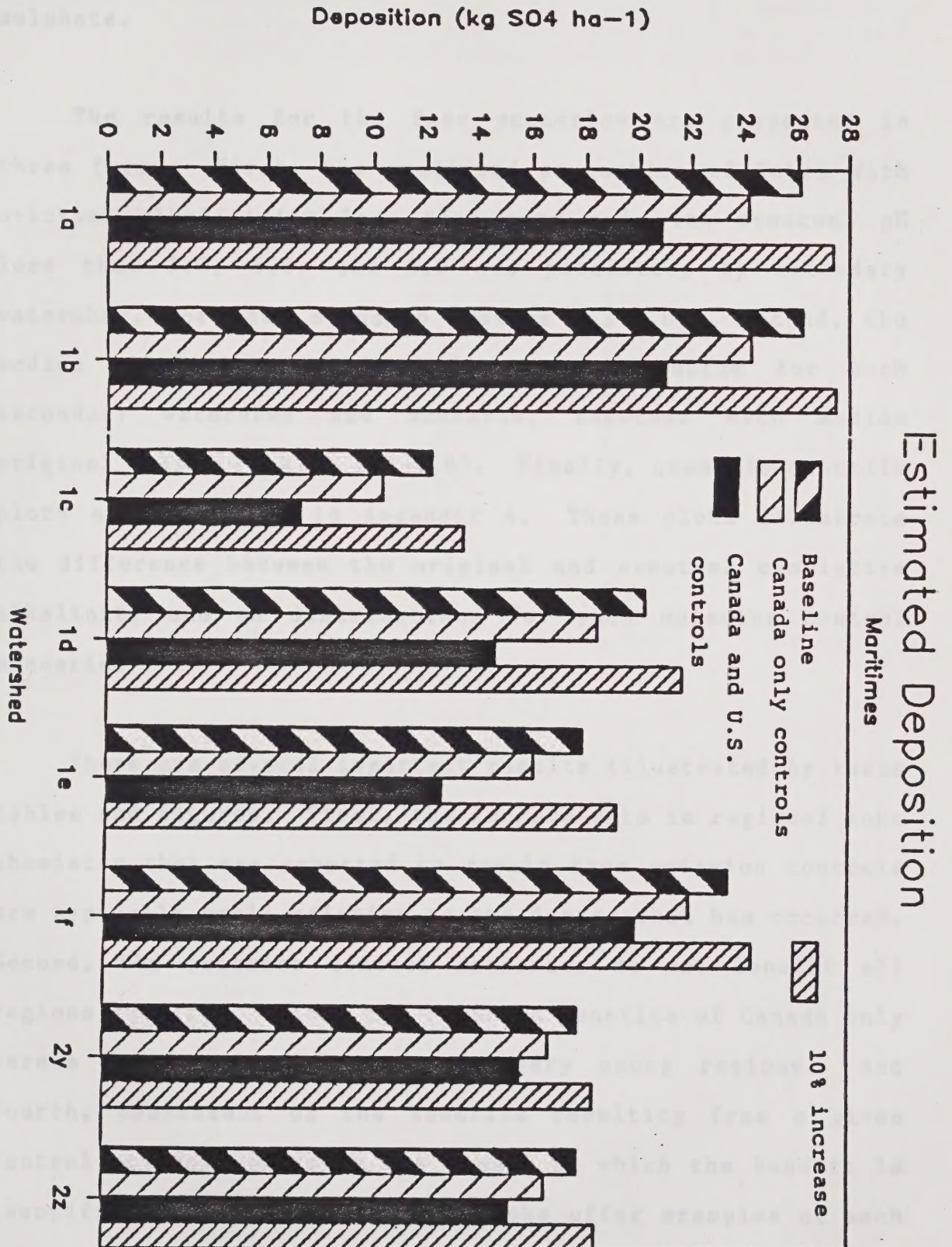


Figure 4.7: Predicted wet sulphate deposition values, by Maritime secondary watersheds, for each scenario.

shown) is assumed to change in direct proportion to wet sulphate.

The results for the four scenarios are presented in three forms. First, the predicted proportion of lakes with eventual alkalinities less than zero and with eventual pH less than 5.0, 5.5, and 6.0 are presented, by secondary watershed, for each scenario (Tables 4.3-4.6). Second, the median alkalinity and pH values are presented for each secondary watershed and scenario, together with median original values (Tables 4.7-4.8). Finally, quantile-quantile plots are presented in Appendix A. These plots illustrate the difference between the original and eventual cumulative alkalinity and pH distributions for each emission control scenario.

There are several important results illustrated by these tables and figures. First, the improvements in regional lake chemistry that are expected to result from emission controls are typically small relative to the damage that has occurred. Second, the emission control scenarios do not benefit all regions equally. Third, the relative benefits of Canada only versus Canada and U.S. controls vary among regions. And fourth, assessment of the benefits resulting from a given control action depends on the manner in which the benefit is quantified. The following paragraphs offer examples of each of these key points.

The first point is best illustrated by considering the

Table 4.3: Proportion of lakes, by secondary watershed, with predicted eventual alkalinity < 0 for the 1980 baseline and emission control scenarios.

Wshed	1980-Base	Canada Only	Canada and US	Worse by 10%
Ontario				
1/2A	0.00	0.00	0.00	0.00
1/2B	0.02	0.02	0.00	0.02
1/2C	0.25	0.24	0.20	0.29
1/2D	0.25	0.15	0.07	0.38
1/2E	0.50	0.25	0.16	0.59
1/2H	0.38	0.33	0.28	0.41
1/2J	0.06	0.06	0.00	0.08
1/2K	0.39	0.36	0.20	0.43
1/4G	0.00	0.00	0.00	0.00
1/4J	0.00	0.00	0.00	0.00
1/4L	0.01	0.01	0.01	0.01
1/4M	0.01	0.01	0.01	0.01
1/4N	0.00	0.00	0.00	0.00
1/5P	0.01	0.01	0.00	0.02
1/5Q	0.00	0.00	0.00	0.00
1/5R	0.00	0.00	0.00	0.00
Quebec				
2/2J	0.02	0.00	0.00	0.02
2/2K	0.08	0.04	0.02	0.17
2/2L	0.10	0.07	0.04	0.10
2/2N	0.09	0.05	0.05	0.12
2/2O	0.02	0.00	0.00	0.04
2/2P	0.06	0.06	0.04	0.08
2/2R	0.08	0.00	0.00	0.14
2/2S	0.39	0.11	0.09	0.39
2/2T	0.05	0.05	0.05	0.05
2/2U	0.05	0.05	0.05	0.05
2/2V	0.02	0.02	0.02	0.02
2/2W	0.02	0.02	0.02	0.02
2/2X	0.02	0.02	0.02	0.02
2/3A	0.13	0.06	0.00	0.15
2/3B	0.03	0.00	0.00	0.05
Maritimes				
3/1A	0.33	0.33	0.30	0.36
3/1B	0.29	0.28	0.12	0.29
3/1D	0.01	0.01	0.01	0.09
3/1E	0.50	0.50	0.50	0.50
3/1F	0.01	0.01	0.10	0.01
3/2Y	0.08	0.08	0.08	0.08
3/2Z	0.06	0.06	0.06	0.06

Table 4.4: Proportion of lakes, by secondary watershed with predicted eventual pH < 5.0 for the 1980 baseline and emission control scenarios.

Wshed	1980-Base	Canada Only	Canada and US	Worse by 10%
Ontario				
1/2A	0.000	0.000	0.000	0.000
1/2B	0.016	0.014	0.012	0.052
1/2C	0.244	0.232	0.220	0.528
1/2D	0.163	0.144	0.100	0.528
1/2E	0.400	0.232	0.196	0.643
1/2H	0.382	0.313	0.290	0.456
1/2J	0.064	0.038	0.014	0.248
1/2K	0.391	0.299	0.225	0.534
1/4G	0.006	0.006	0.006	0.006
1/4J	0.006	0.006	0.006	0.006
1/4L	0.013	0.013	0.013	0.018
1/4M	0.013	0.013	0.013	0.013
1/4N	0.006	0.000	0.000	0.010
1/5P	0.009	0.009	0.011	0.020
1/5Q	0.000	0.000	0.000	0.000
1/5R	0.000	0.000	0.000	0.000
Quebec				
2/2J	0.011	0.001	0.000	0.070
2/2K	0.042	0.041	0.029	0.314
2/2L	0.073	0.052	0.047	0.134
2/2N	0.050	0.050	0.050	0.400
2/2O	0.000	0.000	0.000	0.061
2/2P	0.060	0.045	0.058	0.340
2/2R	0.000	0.000	0.000	0.139
2/2S	0.089	0.089	0.089	0.392
2/2T	0.051	0.051	0.051	0.380
2/2U	0.051	0.051	0.051	0.380
2/2V	0.024	0.024	0.024	0.500
2/2W	0.024	0.024	0.024	0.500
2/2X	0.024	0.021	0.024	0.500
2/3A	0.105	0.016	0.023	0.229
2/3B	0.015	0.000	0.000	0.125
Maritimes				
3/1A	0.331	0.302	0.325	0.464
3/1B	0.217	0.137	0.229	0.337
3/1D	0.013	0.013	0.013	0.013
3/1E	0.504	0.501	0.000	0.504
3/1F	0.014	0.014	0.014	0.014
3/2Y	0.077	0.069	0.098	0.223
3/2Z	0.062	0.041	0.063	0.438

Table 4.5: Proportion of lakes, by secondary watershed, with predicted eventual pH < 5.5 for the 1980 baseline and emission control scenarios.

Wshed	1980-Base	Canada Only	Canada and US	Worse by 10%
Ontario				
1/2A	0.000	0.000	0.000	0.000
1/2B	0.019	0.015	0.012	0.021
1/2C	0.270	0.236	0.220	0.324
1/2D	0.327	0.146	0.100	0.461
1/2E	0.545	0.236	0.196	0.599
1/2H	0.399	0.317	0.290	0.416
1/2J	0.071	0.047	0.014	0.104
1/2K	0.407	0.320	0.225	0.443
1/4G	0.006	0.006	0.006	0.006
1/4J	0.006	0.006	0.006	0.006
1/4L	0.015	0.013	0.013	0.016
1/4M	0.013	0.013	0.013	0.013
1/4N	0.009	0.001	0.000	0.009
1/5P	0.017	0.010	0.011	0.018
1/5Q	0.000	0.000	0.000	0.000
1/5R	0.000	0.000	0.000	0.000
Quebec				
2/2J	0.024	0.004	0.000	0.024
2/2K	0.138	0.042	0.029	0.215
2/2L	0.104	0.081	0.047	0.112
2/2N	0.118	0.050	0.050	0.164
2/2O	0.038	0.007	0.000	0.048
2/2P	0.081	0.060	0.058	0.121
2/2R	0.132	0.039	0.000	0.139
2/2S	0.392	0.300	0.089	0.392
2/2T	0.067	0.051	0.051	0.059
2/2U	0.064	0.051	0.051	0.152
2/2V	0.024	0.024	0.024	0.024
2/2W	0.024	0.024	0.024	0.024
2/2X	0.024	0.024	0.024	0.024
2/3A	0.148	0.099	0.023	0.153
2/3B	0.058	0.013	0.000	0.067
Maritimes				
3/1A	0.351	0.333	0.325	0.386
3/1B	0.290	0.289	0.229	0.290
3/1D	0.219	0.066	0.013	0.312
3/1E	0.504	0.504	0.504	0.504
3/1F	0.014	0.014	0.014	0.047
3/2Y	0.078	0.198	0.098	0.078
3/2Z	0.063	0.154	0.063	0.063

Table 4.6: Proportion of lakes, by secondary watershed, with predicted eventual pH < 6.0 for the 1980 baseline and emission control scenarios.

Wshed	1980-Base	Canada Only	Canada and US	Worse by 10%
Ontario				
1/2A	0.000	0.000	0.000	0.000
1/2B	0.037	0.028	0.017	0.052
1/2C	0.512	0.356	0.246	0.528
1/2D	0.528	0.238	0.148	0.528
1/2E	0.631	0.407	0.245	0.643
1/2H	0.443	0.382	0.333	0.456
1/2J	0.200	0.064	0.064	0.248
1/2K	0.495	0.391	0.377	0.534
1/4G	0.006	0.006	0.006	0.006
1/4J	0.006	0.006	0.006	0.006
1/4L	0.018	0.017	0.013	0.018
1/4M	0.013	0.013	0.013	0.013
1/4N	0.009	0.009	0.009	0.010
1/5P	0.020	0.020	0.020	0.020
1/5Q	0.000	0.000	0.000	0.000
1/5R	0.000	0.000	0.000	0.000
Quebec				
2/2J	0.047	0.024	0.005	0.070
2/2K	0.314	0.084	0.042	0.314
2/2L	0.121	0.108	0.093	0.134
2/2N	0.400	0.254	0.085	0.400
2/2O	0.061	0.061	0.036	0.061
2/2P	0.270	0.171	0.092	0.340
2/2R	0.139	0.139	0.139	0.139
2/2S	0.392	0.392	0.392	0.392
2/2T	0.380	0.380	0.242	0.380
2/2U	0.380	0.380	0.380	0.380
2/2V	0.500	0.500	0.213	0.500
2/2W	0.500	0.451	0.205	0.500
2/2X	0.489	0.354	0.110	0.500
2/3A	0.192	0.153	0.153	0.229
2/3B	0.125	0.153	0.124	0.125
Maritimes				
3/1A	0.457	0.448	0.370	0.464
3/1B	0.334	0.290	0.290	0.337
3/1D	0.330	0.330	0.327	0.330
3/1E	0.848	0.848	0.504	0.848
3/1F	0.354	0.354	0.354	0.354
3/2Y	0.213	0.198	0.183	0.223
3/2Z	0.360	0.154	0.063	0.438

Table 4.7: Median alkalinity values by secondary watershed originally and for each scenario.

Wshed	Original	1980-Base	Canada Only	Canada and US	Worse by 10%
Total	100.3	62.2	64.4	79.7	60.3
Ontario	305.6	302.7	304.3	304.5	302.5
1/2A	382.5	382.5	382.5	382.5	381.4
1/2B	255.0	255.0	255.0	255.0	255.0
1/2C	115.0	26.8	47.5	55.0	25.2
1/2D	117.6	26.8	55.0	57.6	24.0
1/2E	109.7	0.0	30.0	47.4	-4.6
1/2H	165.0	90.0	110.0	120.0	90.0
1/2J	147.8	87.8	100.0	117.8	87.3
1/2K	135.7	23.6	46.5	70.0	15.0
1/4G	404.7	404.7	404.7	404.7	404.7
1/4J	404.7	404.7	404.7	404.7	404.7
1/4L	402.6	402.6	402.6	402.6	402.6
1/4M	402.6	402.6	402.6	402.6	402.6
1/4N	402.6	402.6	402.6	402.6	402.6
1/5P	221.3	221.3	221.3	221.3	221.3
1/5Q	290.8	290.8	290.8	290.8	290.8
1/5R	290.8	290.8	290.8	290.8	290.8
Quebec	91.3	53.8	55.7	62.7	52.7
2/2J	137.7	93.0	107.1	77.7	83.3
2/2K	137.7	90.0	120.0	120.0	90.0
2/2L	175.0	144.5	145.0	145.0	144.5
2/2N	98.1	40.0	60.0	67.9	37.9
2/2O	168.5	138.5	138.5	140.0	138.5
2/2P	104.1	63.0	71.4	74.1	58.2
2/2R	111.4	81.4	81.4	81.4	81.4
2/2S	83.6	53.6	53.6	53.6	52.5
2/2T	84.0	54.0	54.0	54.0	54.0
2/2U	84.0	54.0	54.0	54.0	54.0
2/2V	60.0	30.0	30.0	30.0	30.0
2/2W	60.0	30.0	30.0	30.0	30.0
2/2X	60.0	30.0	30.0	30.0	30.0
2/3A	111.4	81.4	81.4	81.4	79.4
2/3B	111.4	81.4	81.4	88.1	81.4
Maritimes	78.4	47.8	48.0	61.6	47.7
3/1A	92.7	35.6	39.2	62.7	33.5
3/1B	92.7	62.7	62.7	62.7	62.7
3/1D	110.0	80.0	78.0	80.0	78.0
3/1E	30.0	< 0	< 0	< 0	< 0
3/1F	85.0	58.0	58.0	58.0	58.0
3/2Y	94.1	65.0	65.6	86.7	64.7
3/2Z	63.8	33.8	33.8	39.5	33.8

Table 4.8: Median pH values by secondary watershed originally and for each scenario.

Wshed	Original	1980-Base	Canada Only	Canada and US	Worse by 10%
Total	6.6	6.4	6.4	6.4	6.4
Ontario	7.1	7.1	7.1	7.1	7.1
1/2A	7.2	7.2	7.2	7.2	7.2
1/2B	7.0	7.0	7.0	7.0	7.0
1/2C	6.7	6.0	6.2	6.4	5.9
1/2D	6.7	5.9	6.2	6.4	5.6
1/2E	6.7	5.4	6.1	6.3	5.2
1/2H	6.8	6.5	6.7	6.7	6.5
1/2J	6.8	6.6	6.6	6.7	6.6
1/2K	6.8	6.0	6.3	6.5	5.8
1/4G	7.3	7.3	7.3	7.3	7.3
1/4J	7.3	7.3	7.3	7.3	7.3
1/4L	7.3	7.3	7.3	7.3	7.3
1/4M	7.3	7.3	7.3	7.3	7.3
1/4N	7.3	7.3	7.3	7.3	7.3
1/5P	7.0	6.9	6.9	6.9	6.9
1/5Q	7.1	7.1	7.1	7.1	7.1
1/5R	7.1	7.1	7.1	7.1	7.1
Quebec	6.6	6.3	6.4	6.4	6.3
2/2J	6.8	6.5	6.6	6.7	6.5
2/2K	6.8	6.6	6.6	6.6	6.6
2/2L	6.9	6.8	6.8	6.8	6.8
2/2N	6.6	6.3	6.3	6.5	6.3
2/2O	6.9	6.7	6.8	6.8	6.7
2/2P	6.7	6.4	6.4	6.5	6.4
2/2R	6.7	6.5	6.5	6.5	6.5
2/2S	6.6	6.2	6.3	6.4	6.2
2/2T	6.6	6.4	6.4	6.4	6.4
2/2U	6.6	6.4	6.4	6.4	6.4
2/2V	6.4	6.2	6.2	6.2	6.2
2/2W	6.4	6.2	6.2	6.2	6.2
2/2X	6.4	6.2	6.2	6.2	6.2
2/3A	6.7	6.5	6.5	6.5	6.5
2/3B	6.7	6.5	6.5	6.5	6.5
Maritimes	6.5	6.3	6.3	6.3	6.3
3/1A	6.6	6.2	6.2	6.3	6.2
3/1B	6.6	6.4	6.4	6.4	6.4
3/1D	6.7	6.5	6.5	6.5	6.5
3/1E	6.1	5.4	5.4	5.7	5.3
3/1F	6.6	6.4	6.4	6.4	6.4
3/2Y	6.6	6.4	6.4	6.4	6.4
3/2Z	6.4	6.2	6.2	6.2	6.2

median alkalinity values. Averaged over all of eastern Canada, the decrease in median alkalinity from the original state to the 1980 baseline eventual state is $38.1 \mu\text{eq.L}^{-1}$. With Canada only controls, the decrease is only reduced to $35.9 \mu\text{eq.L}^{-1}$ (i.e., a 5.7% improvement, relative to the original state). Even the Canada and U.S. controls only result in a 45.9% improvement. There are exceptions to this rule (e.g., Newfoundland watershed 2Y with Canada and U.S. controls), but the overall results indicate that emission controls, especially in Canada alone, will only allow a relatively small proportion of the total estimated damage to be reversed.

Table 4.7 can also be used to illustrate the second point: that emission control benefits are not distributed uniformly across all regions. Canada only controls are predicted to allow substantial improvements in the sensitive, high deposition watersheds of Ontario, but will have little impact on large areas of Quebec and the Maritimes. That the pattern changes when Canada and U.S. controls are simulated, illustrates the third point. The Maritime provinces stand to benefit far more from the addition of the U.S. controls, relatively speaking, than does Ontario. For example, Canada only controls have very little impact on Newfoundland lakes, whereas Canada and U.S. controls lead to marked improvements (especially in watershed 2Y). In Ontario, the addition of U.S. controls results in significant improvement to the severely affected watersheds, but the magnitude of these additional improvements is consistently smaller than that

resulting from Canada only controls.

The fourth point noted above is central to the issue of identifying acceptable target loadings or emission reductions. When comparing the consequences of a given control strategy among regions, the results of the comparison will depend on the metric that is chosen to describe impacts (or benefits). Consider the results presented in Tables 4.4-4.5 for watershed 2C in Ontario. Canada only controls result in only a 4.9% decrease in the proportion of lakes with pH < 5.0 relative to the baseline (.244-.232), while Canada and U.S. controls result in a 51.6% reduction (.244-.118). Conversely, Canada only controls result in a 12.6% reduction in the proportion of lakes with pH < 5.5, while Canada and U.S. controls yield an 18.5% decrease. Thus, if one were evaluating the relative benefits of Canada only versus Canada and U.S. controls for watershed 2C, the conclusion would depend entirely on which indicator of damage (i.e., lakes with pH < 5.0 or < 5.5) was chosen for the comparison.

These observations highlight the need for better integrated measures of damage due to acidic deposition and recovery due to emission controls. The median alkalinity and pH values presented in Tables 4.7-4.8 are integrated measures, but do not adequately represent subtle, but important changes such as those apparent in the eventual alkalinity and pH distributions of Quebec watershed 2T (Table 4.6). These changes are not evident from Table 4.8. Measures are needed that integrate potential biological damage across the even-

tual pH or alkalinity distributions, using existing knowledge of the pH thresholds for impacts on a range of valued, or indicator species. Minns (1987) provides examples of such measures.

The quantile-quantile (q.q.) plots provide one form of integrated picture of chemical change, since they summarize the entire original and eventual chemical distributions of the region in question. The 1:1 line on these plots is the original distribution plotted against itself. Comparisons of this line to the other lines (original versus scenario X) gives an indication of by how much the distributions have changed.

These comparisons among q.q. lines can be made in different ways, with very different interpretations. For example, the vertical separation of two lines on a q.q. plot indicates the average change in pH (or alkalinity) for all lakes whose original pH was X (Figure 4.8a). This can be repeated for any reference pH. The horizontal separation, on the other hand shows the change in the proportion of lakes whose pH is less than Y, originally versus eventually (Figure 4.8b). Again, the comparison can be made for any reference chemical value. The q.q. plots thus provide a useful policy evaluation tool that does not rely upon a single metric for comparing the results of control actions.

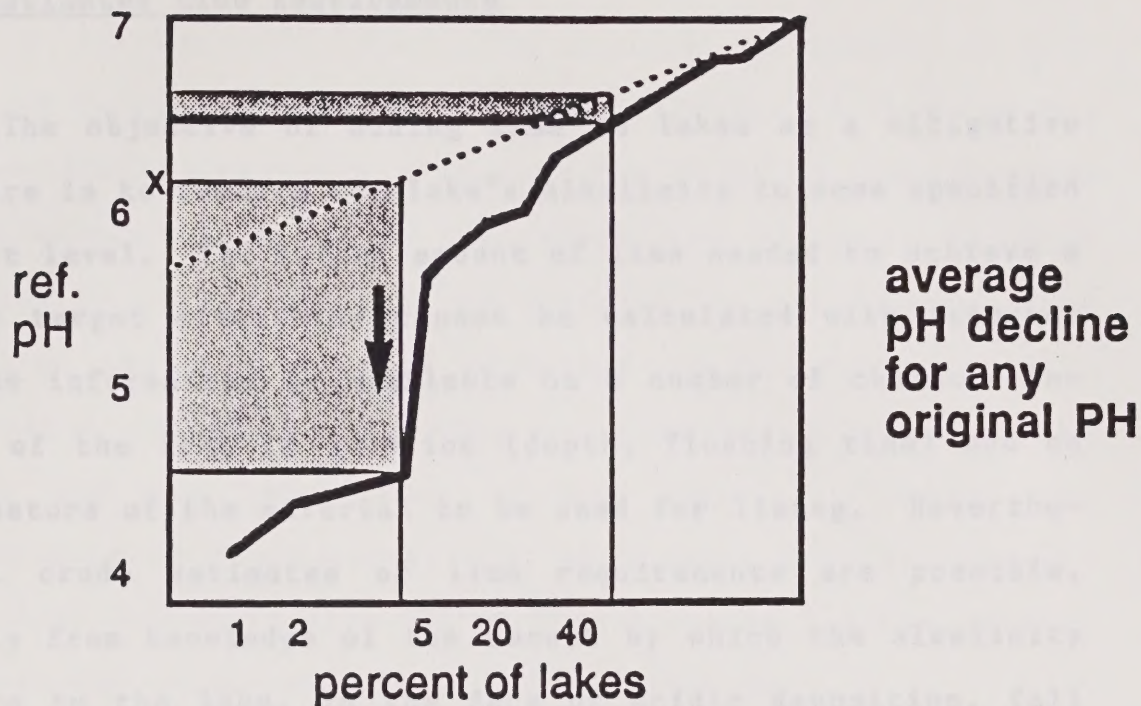


Figure 4.8a: Vertical separation of two lines on a quantile-quantile plot indicating the average change in pH (or alkalinity) for all lakes whose original pH was X.

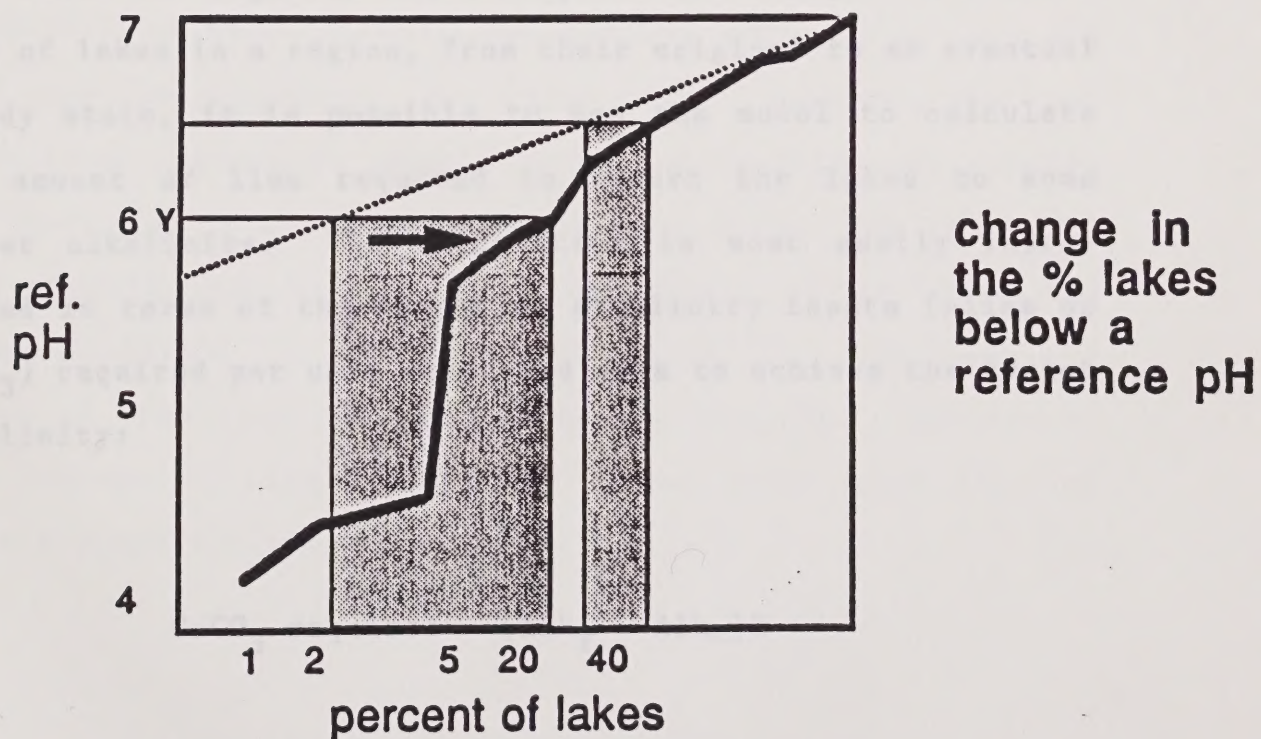


Figure 4.8b: Horizontal separation of two lines on a quantile-quantile plot indicating the change in the proportion of lakes whose pH is less than Y, originally versus eventually.

4.5 Estimated Lime Requirements

The objective of adding lime to lakes as a mitigative measure is to restore the lake's alkalinity to some specified target level. The actual amount of lime needed to achieve a given target alkalinity cannot be calculated with accuracy unless information is available on a number of characteristics of the lake in question (depth, flushing time) and on the nature of the material to be used for liming. Nevertheless, crude estimates of lime requirements are possible, simply from knowledge of the amount by which the alkalinity inputs to the lake, in the face of acidic deposition, fall short of the target alkalinity requirements.

Since the regional model computes the changes in alkalinity of lakes in a region, from their original to an eventual steady state, it is possible to use the model to calculate the amount of lime required to return the lakes to some target alkalinity. The calculation is most easily represented in terms of the amount of alkalinity inputs (=lime as CaCO_3) required per unit watershed area to achieve the target alkalinity:

$$(21) \quad \text{CaCO}_3 \text{ required} = (\text{Alk}_T - \text{Alk}_\infty)R$$

where Alk_T is the target alkalinity. The units of CaCO_3 required are $\text{meq m}^{-2} \cdot \text{yr}^{-1}$.

To estimate the total lime required to achieve certain targets in an entire region, this calculation is repeated for all eventual alkalinity classes. The weighted sum of these requirements (weighted by the proportion of lakes in each alkalinity class) provides an estimate of the average lime required per unit area of watershed in the entire region. The total requirement is thus the product of this average value and the total area of the region. Finally, the requirement is increased by 10%, to account for the observation that typically only 90% of lime added to a lake actually contributes to increasing the lake's alkalinity.

Estimated lime requirements to achieve five alkalinity targets are presented in Table 4.9. The eventual alkalinity distributions used in this calculation were those for the 1980 baseline scenario. The first target requires that all lakes be maintained in their original state (i.e., no alkalinity loss due to acidic sulphate deposition). The remaining four require that all lakes be maintained at or above the specified levels (0, 20, 50 or 100 $\mu\text{eq.L}^{-1}$). Note that the estimated lime requirements are annual figures. The specified amount of lime would have to be added each year to achieve these targets.

Table 4.9: Estimated Lime Requirements (tonnes/year).

Secondary Watershed	Original Alkalinity	Target Alkalinity (µeq/L)			
		0	20	50	100
1a	112470.24	25989.27	42903.94	74238.86	142115.08
1b	54109.58	12174.62	18101.71	33403.48	70139.69
1d	42142.42	0.00	2069.44	10067.01	53066.67
1e	49205.41	0.00	885.44	23016.94	113749.20
1f	21063.90	0.00	698.45	4002.50	28222.94
2y	97118.14	7418.19	18550.28	55394.09	194287.77
2z	106490.76	3616.33	10186.53	91462.41	320731.88
Maritime Total	482600.46	49198.42	93395.80	291585.28	922313.25
2j	20512.91	0.00	16.72	1907.94	12464.61
2k	10773.02	25.03	703.57	2684.73	7343.33
2l	25025.70	1703.67	3204.86	6312.49	15527.29
2n	40821.73	1271.70	4176.45	13949.87	43390.15
2o	20641.68	57.38	767.59	2330.50	9186.34
2p	36443.14	1992.93	4794.71	15462.85	42670.78
2r	51863.70	404.10	7824.29	23097.97	68152.81
2s	22535.50	4402.35	9092.60	17516.68	37424.26
2t	41366.96	5905.44	14011.76	33564.17	83378.25
2u	27319.08	4056.07	9613.53	21963.10	53085.28
2v	25608.62	3081.37	7841.09	23302.80	65359.42
2w	27413.22	3069.55	7700.72	25447.61	73890.10
2x	13996.80	1461.30	3732.13	13304.45	39545.96
3a	22114.86	1160.78	3921.25	10191.27	27465.63
3b	31007.46	154.99	3596.71	13178.39	43738.67
Quebec Total	417444.39	28746.65	80997.97	224214.81	622622.89
2a	9977.60	0.00	0.00	0.00	622.87
2b	28401.08	607.53	1279.41	3800.63	12570.98
2c	88223.78	10763.13	17384.91	35202.33	75818.28
2d	53349.09	4997.12	10061.99	20164.95	43531.49
2e	90569.67	14384.70	23514.39	40372.94	77579.37
2h	100884.05	26911.57	35388.23	50834.13	79718.92
2j	33691.35	642.60	1396.77	5265.60	17494.13
2k	59144.67	10854.59	15003.24	24028.43	41794.98
4g	7530.32	310.37	589.22	1007.83	1704.62
4j	12733.12	526.37	754.51	1097.02	1667.11
4l	32325.05	1045.65	1688.60	2664.63	5318.34
4m	14036.82	570.71	893.06	1387.03	2725.42
4n	6214.93	102.60	310.02	621.06	1356.03
5p	12847.07	192.01	519.98	1185.12	4153.43
5q	6824.91	0.00	0.00	0.00	0.00
5r	1877.83	0.00	0.00	0.00	0.00
Ontario Total	558631.35	71908.93	108784.34	187631.71	366055.97
Overall Total	1,458,676	149,854	283,178	703,432	1,910,992

V LITERATURE CITED

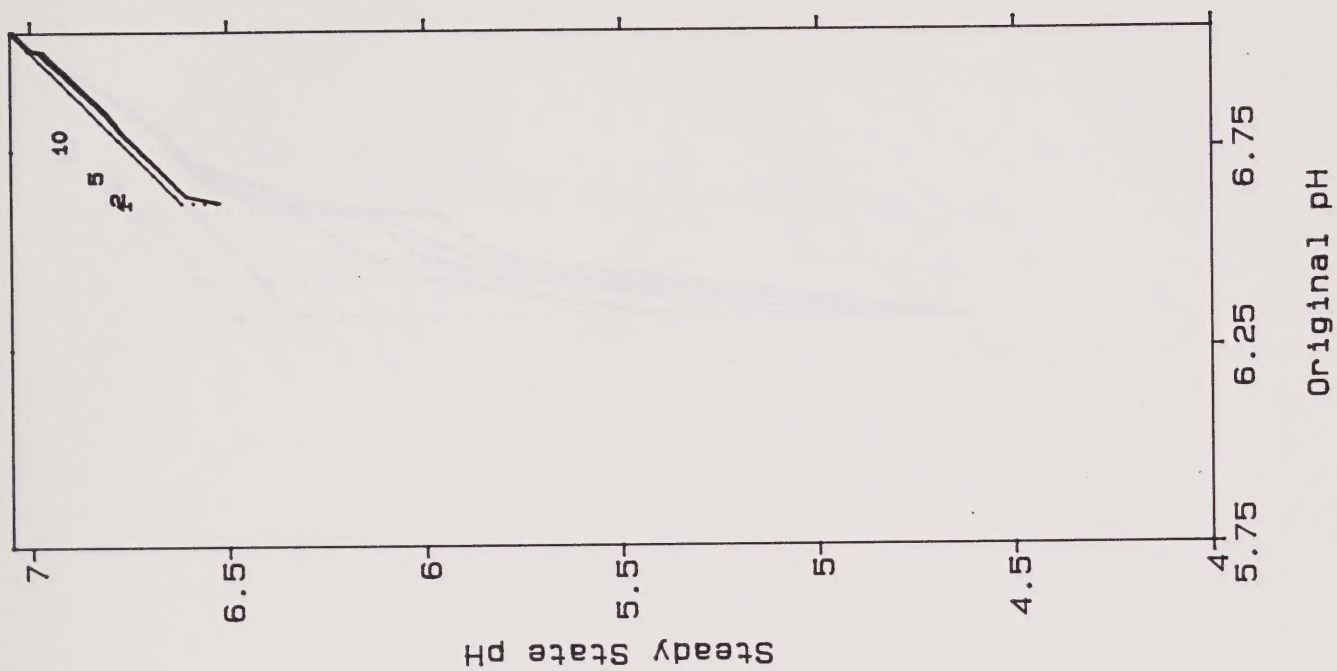
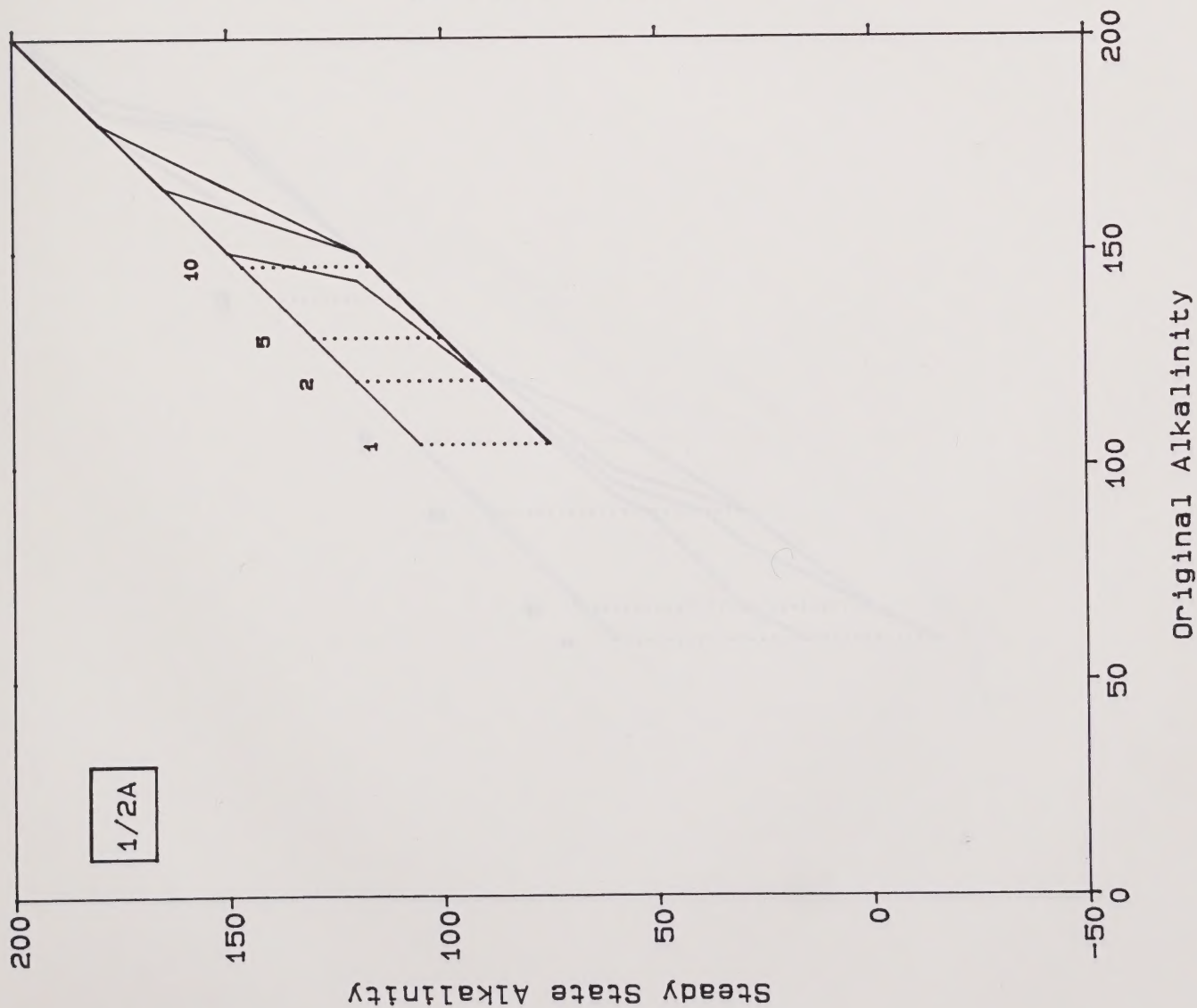
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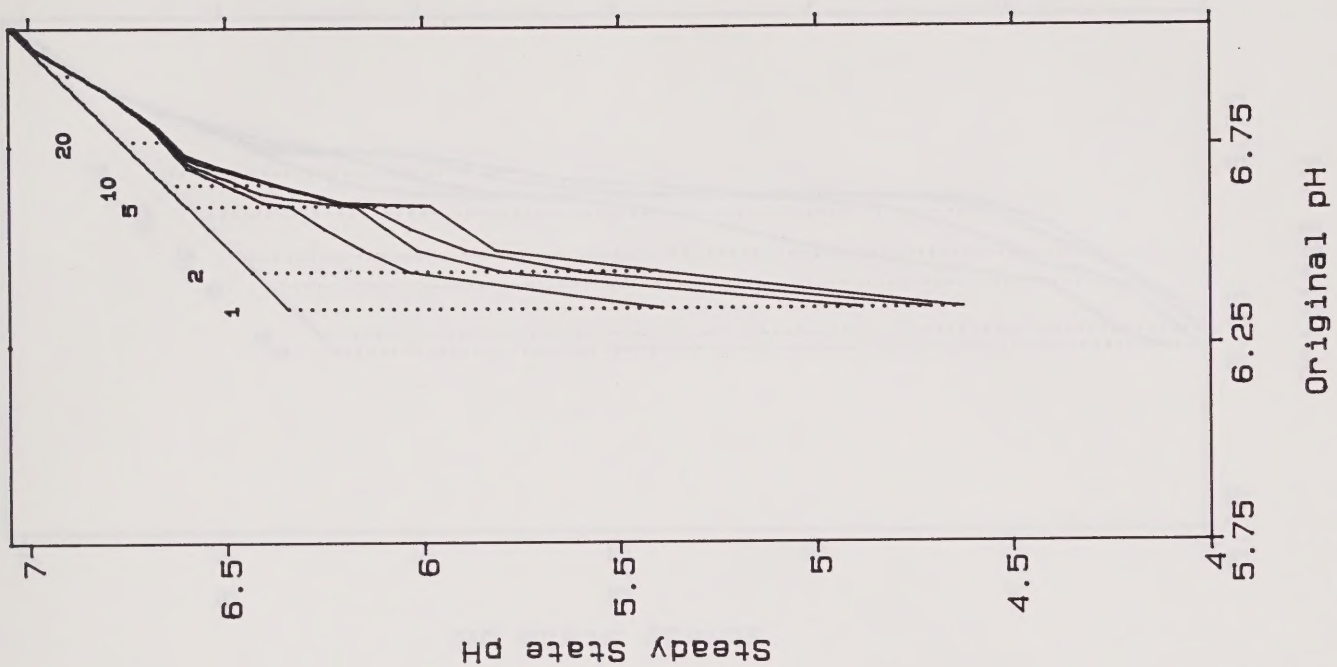
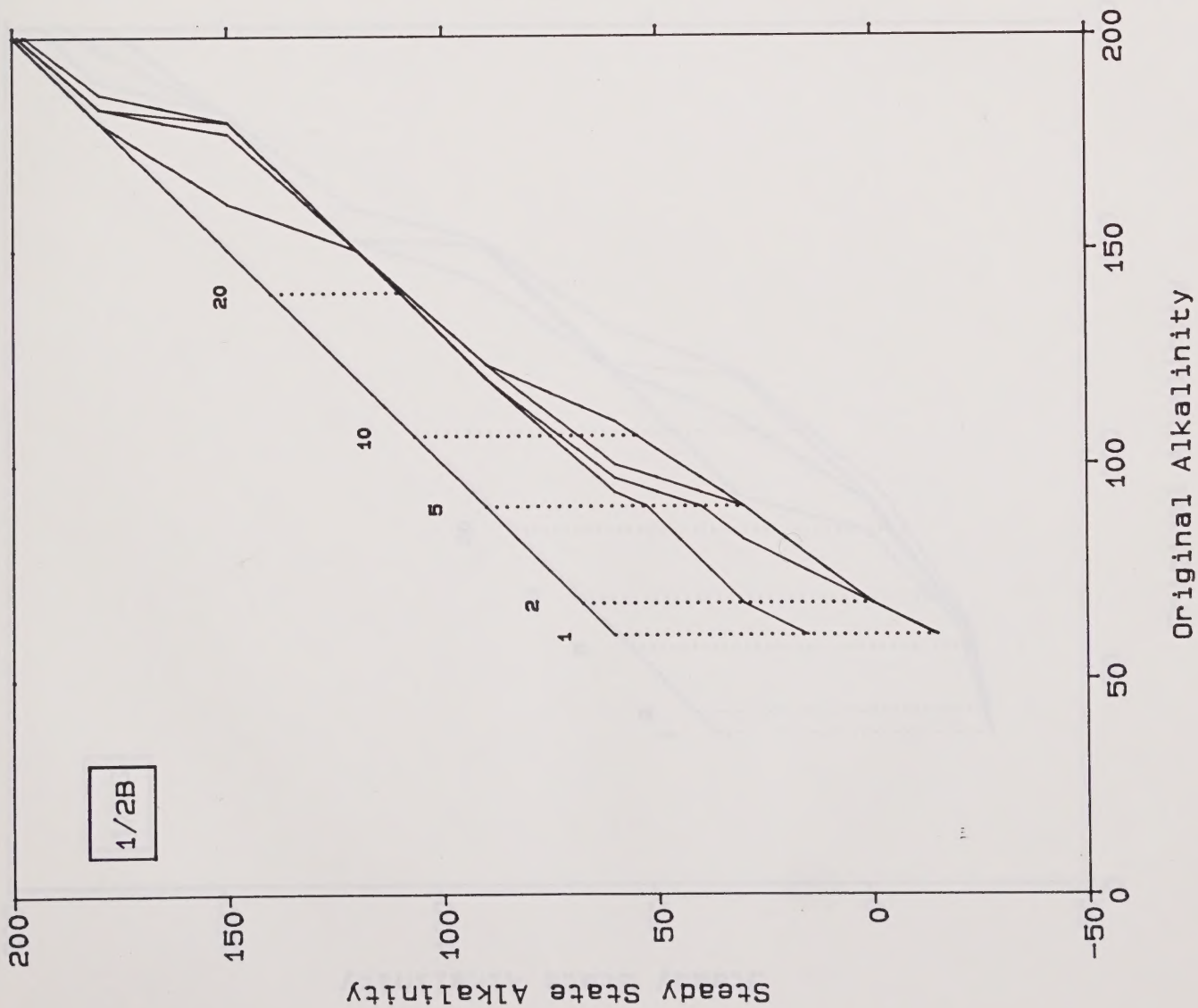
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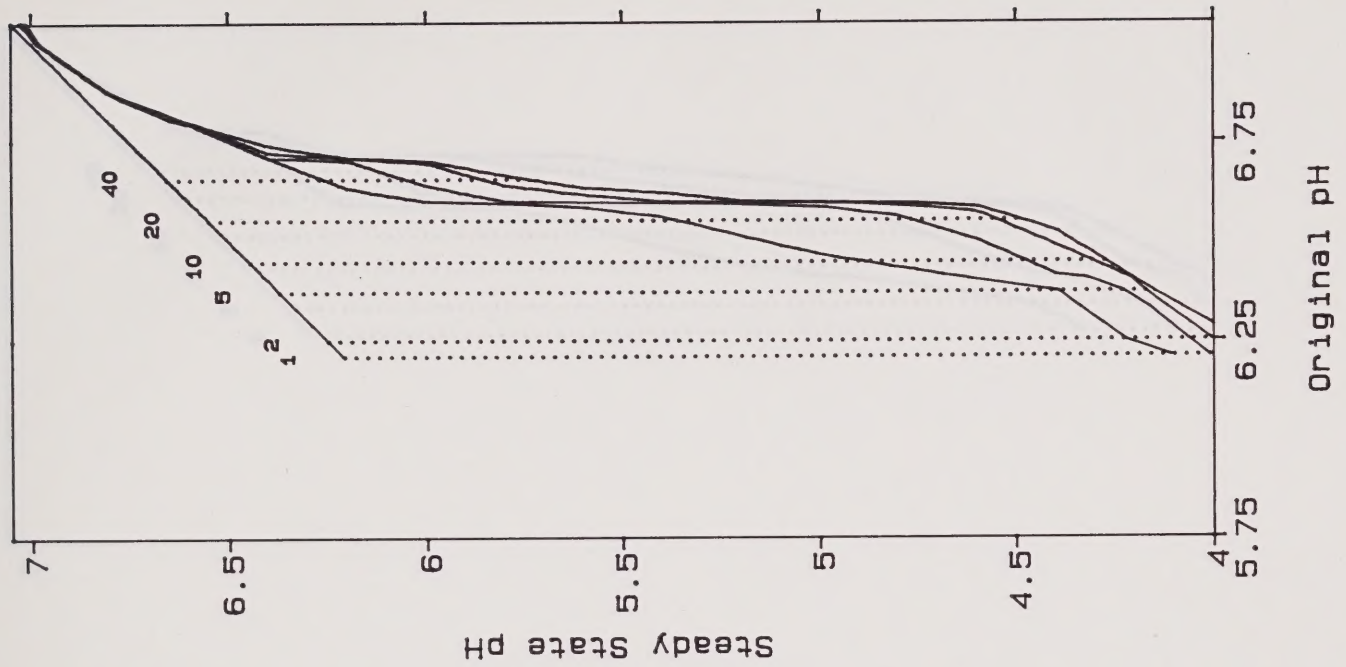
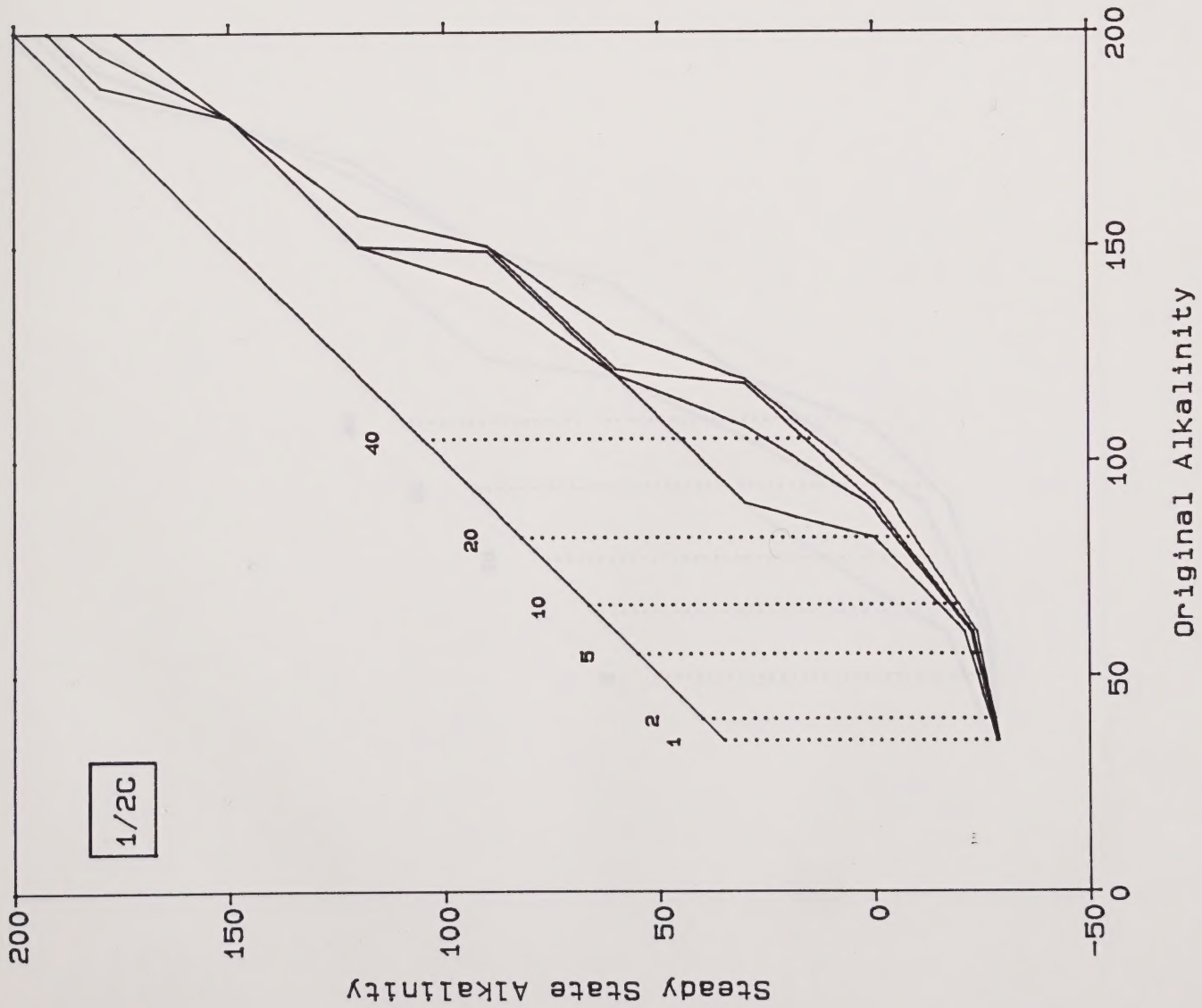
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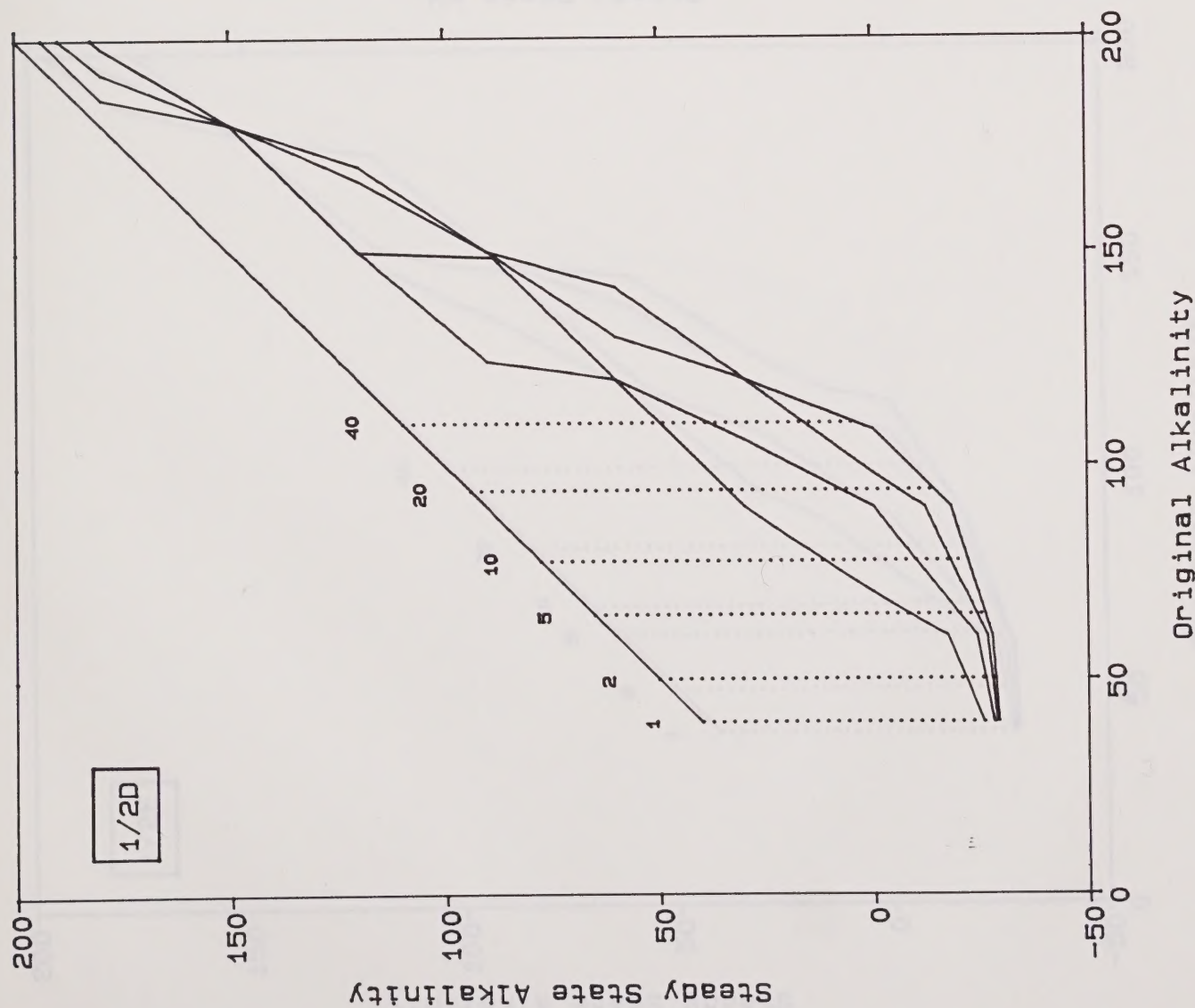
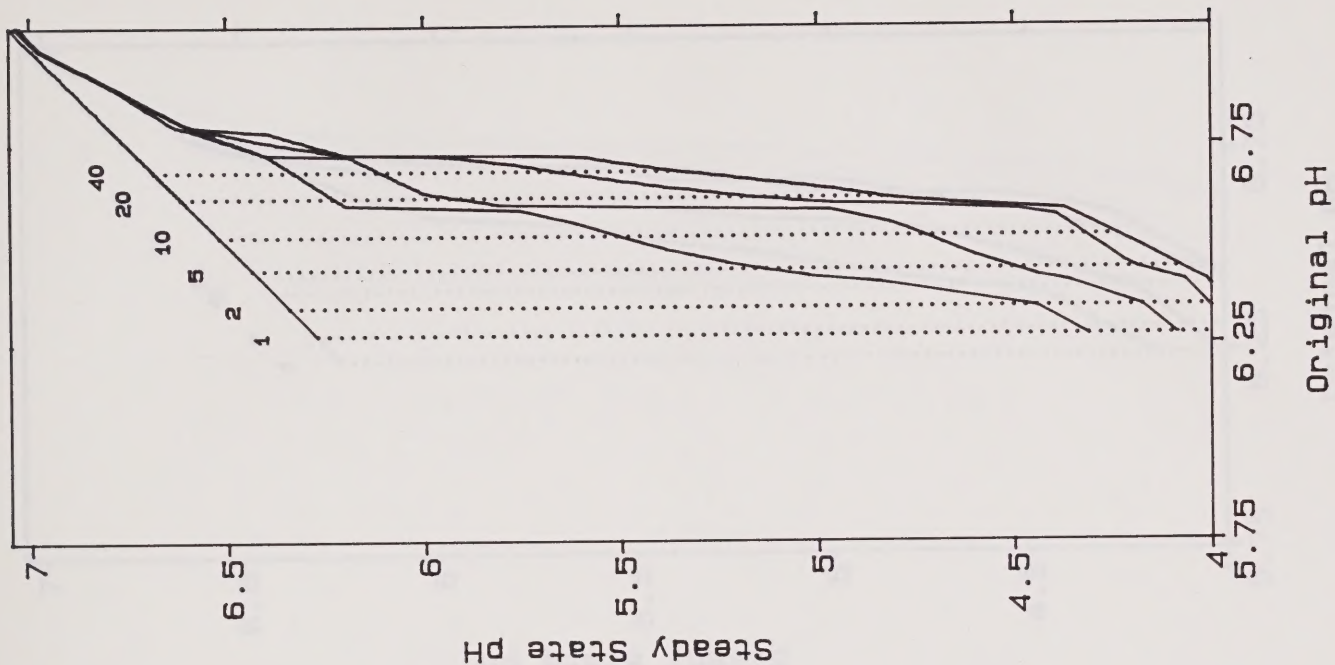
APPENDIX A

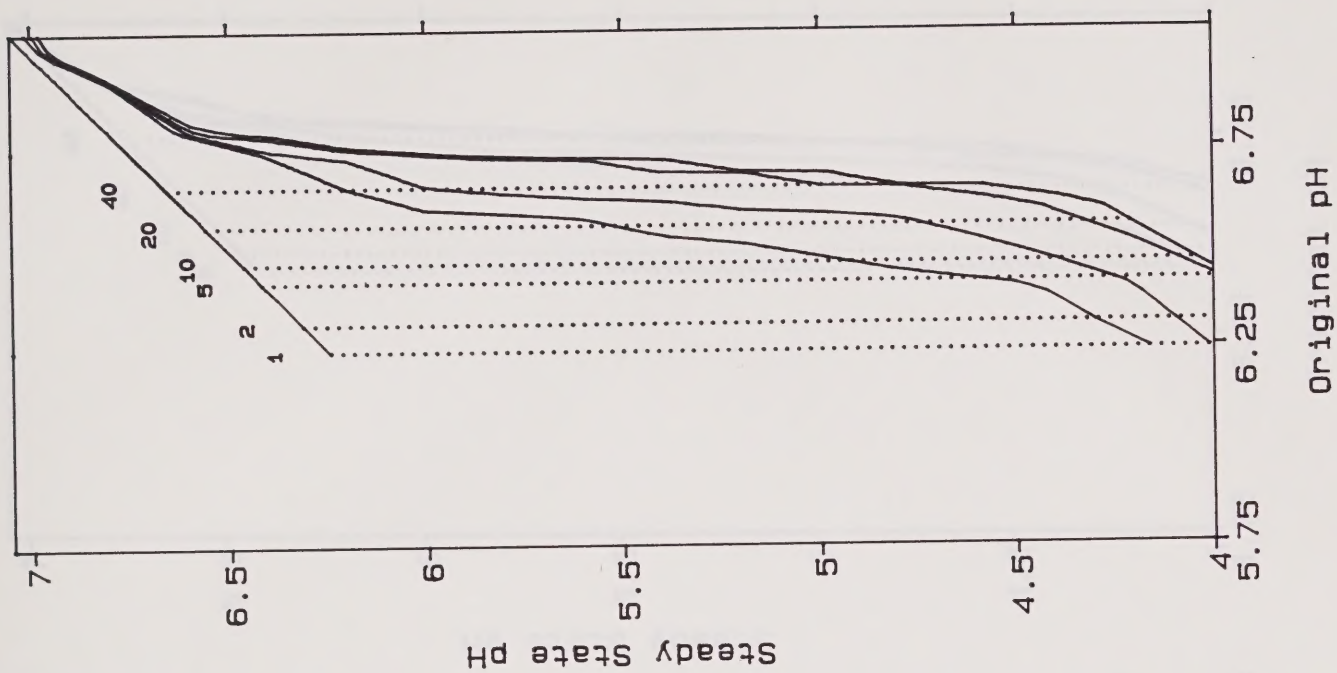
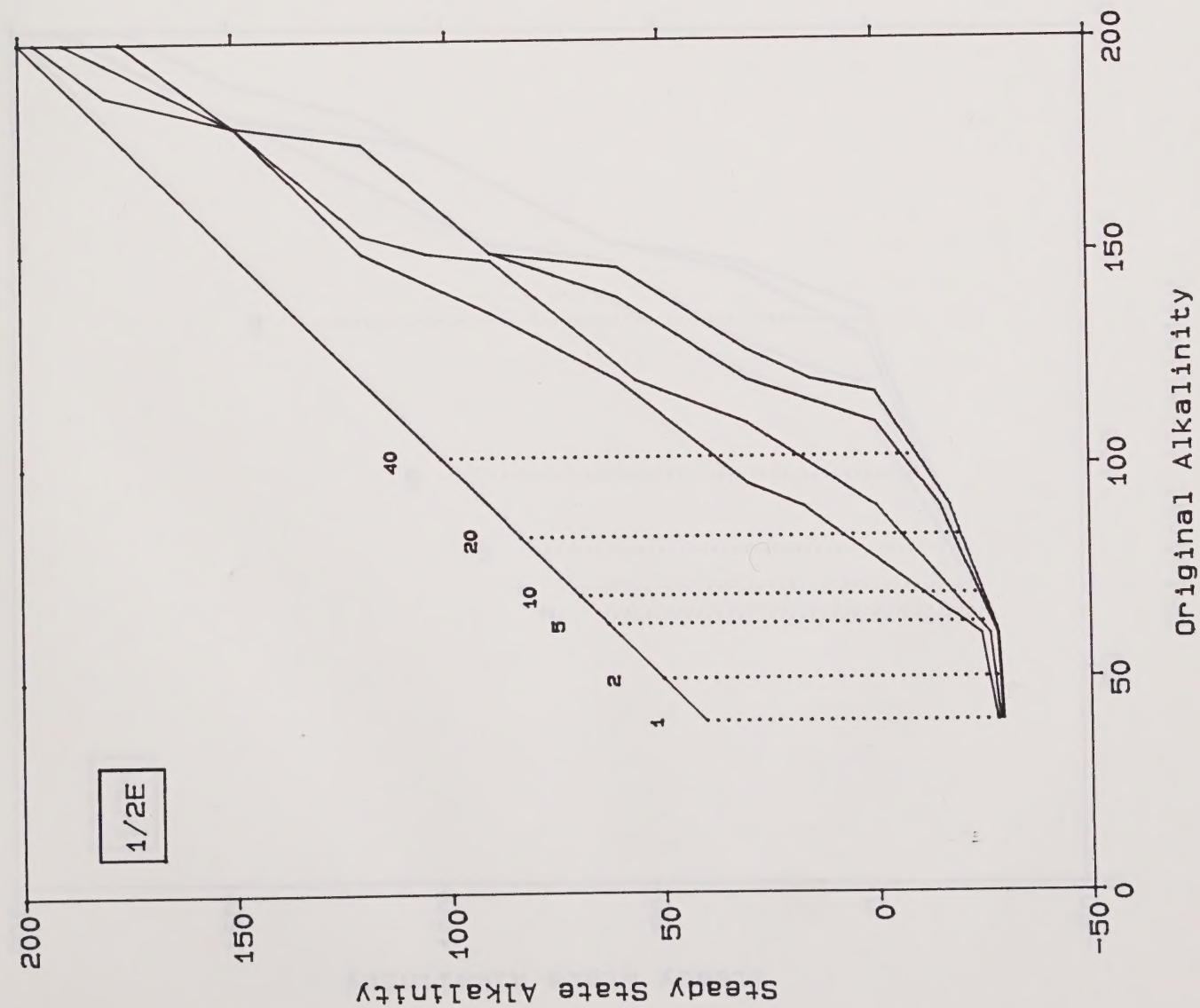
Quantile-quantile plots illustrating the difference between original and eventual cumulative alkalinity and pH distributions for each emission control scenario.

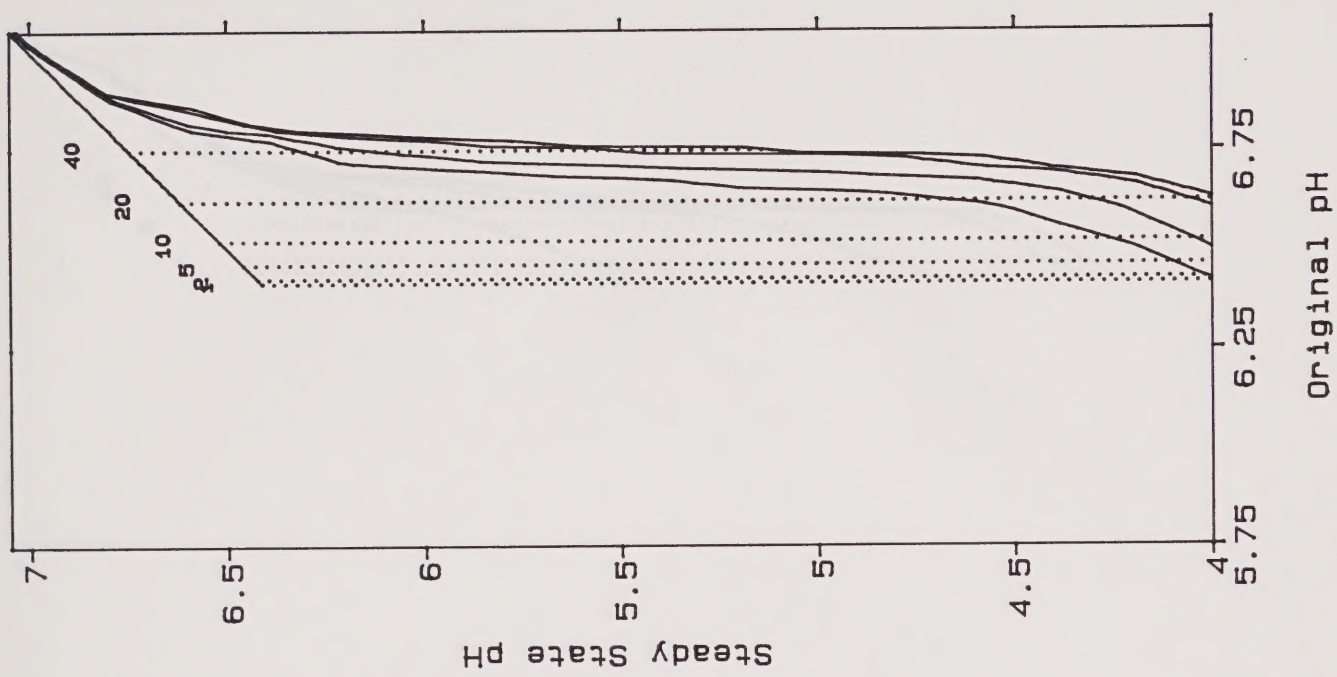
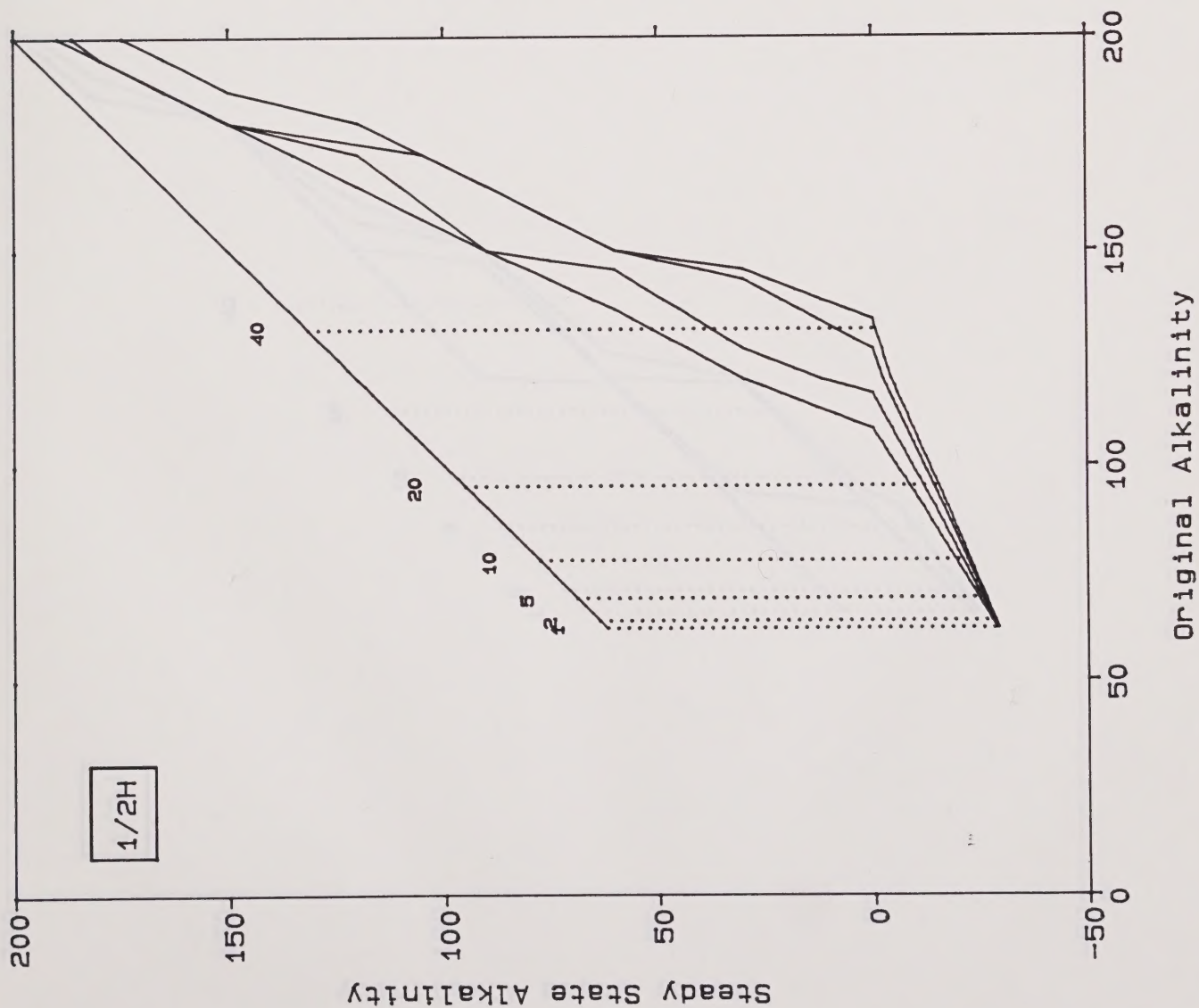


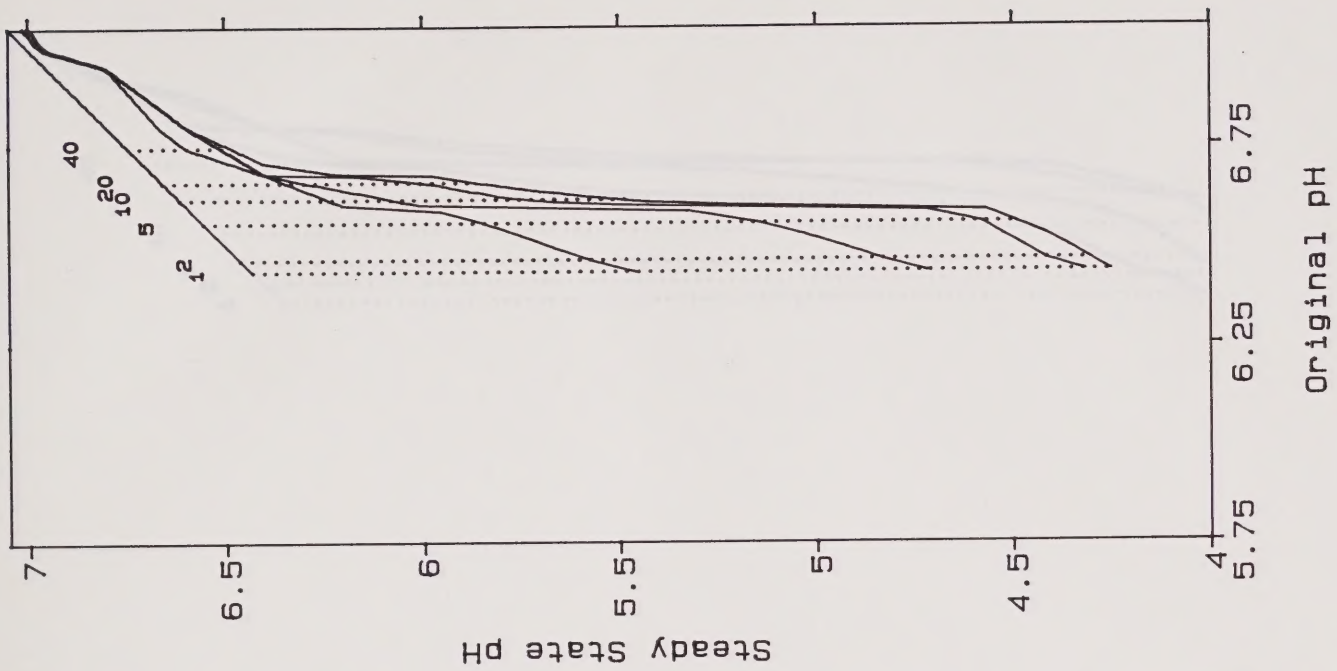
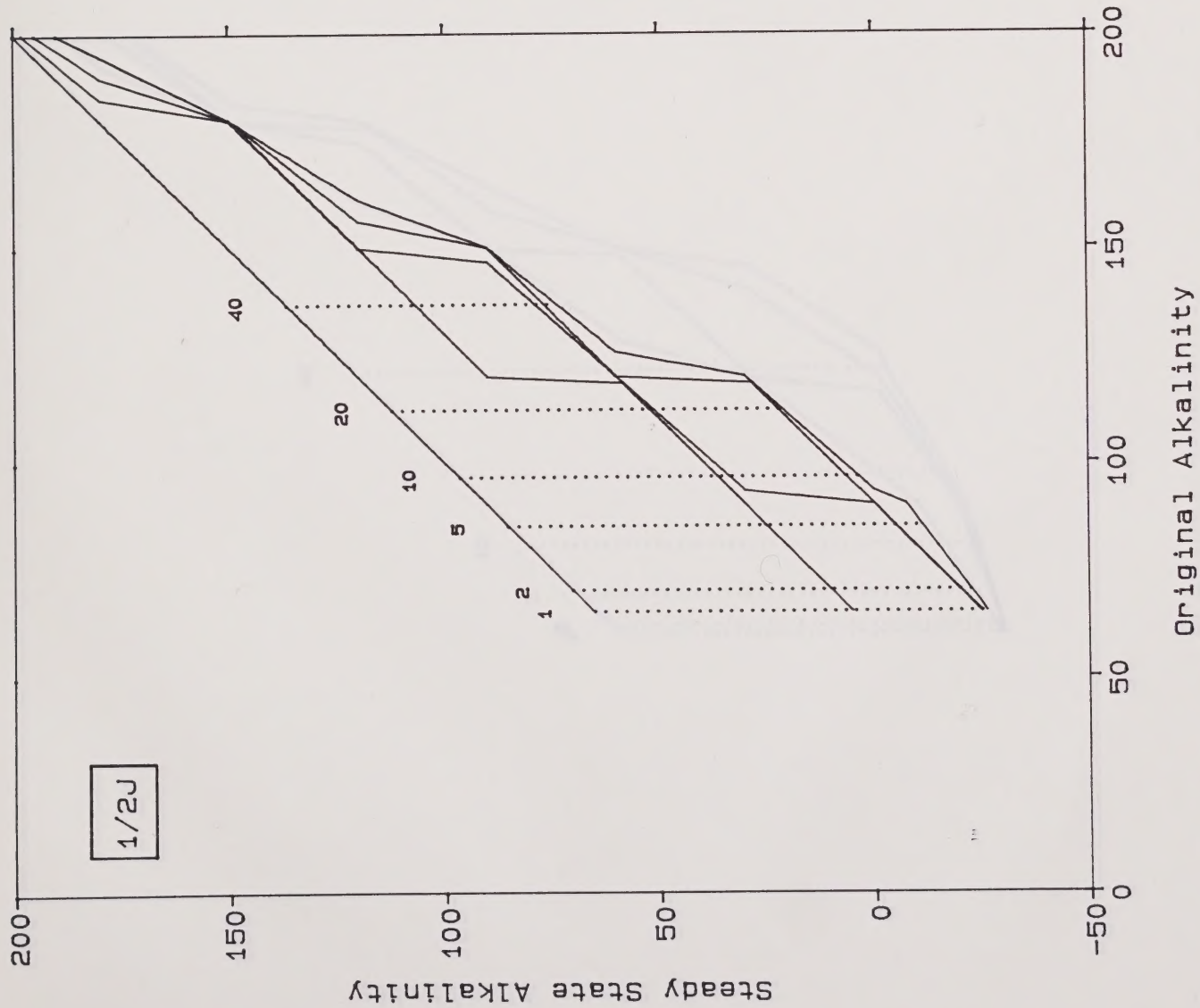


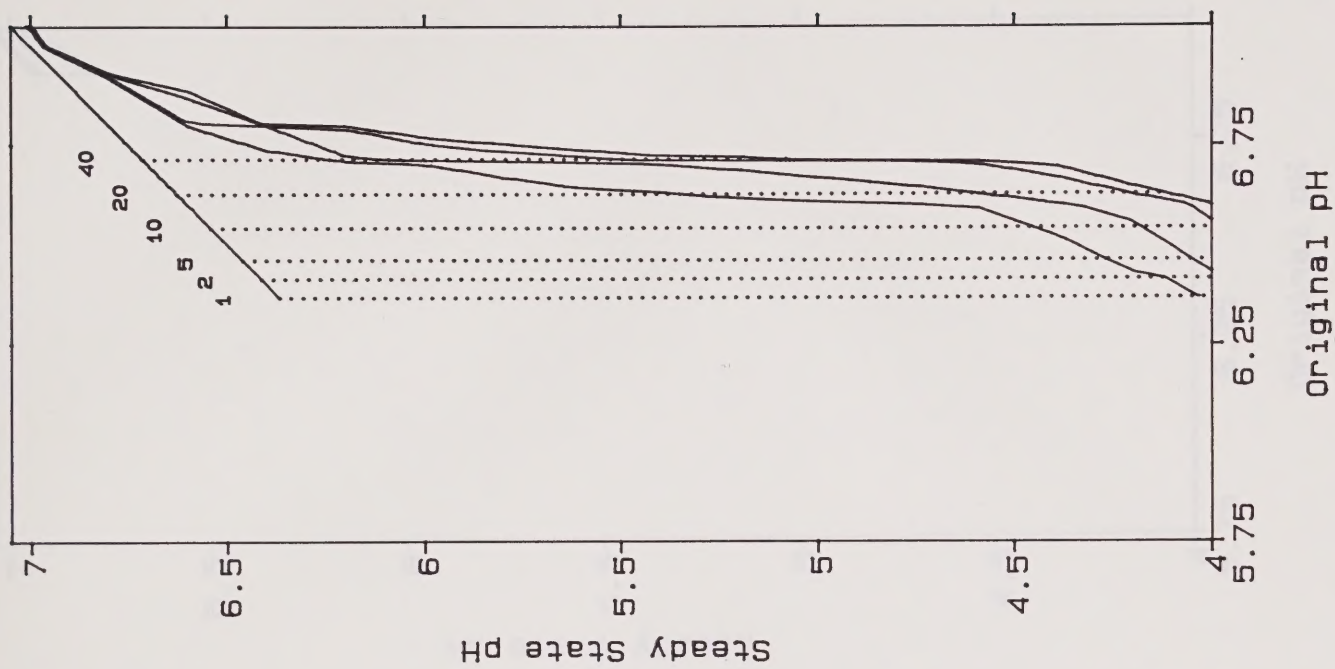
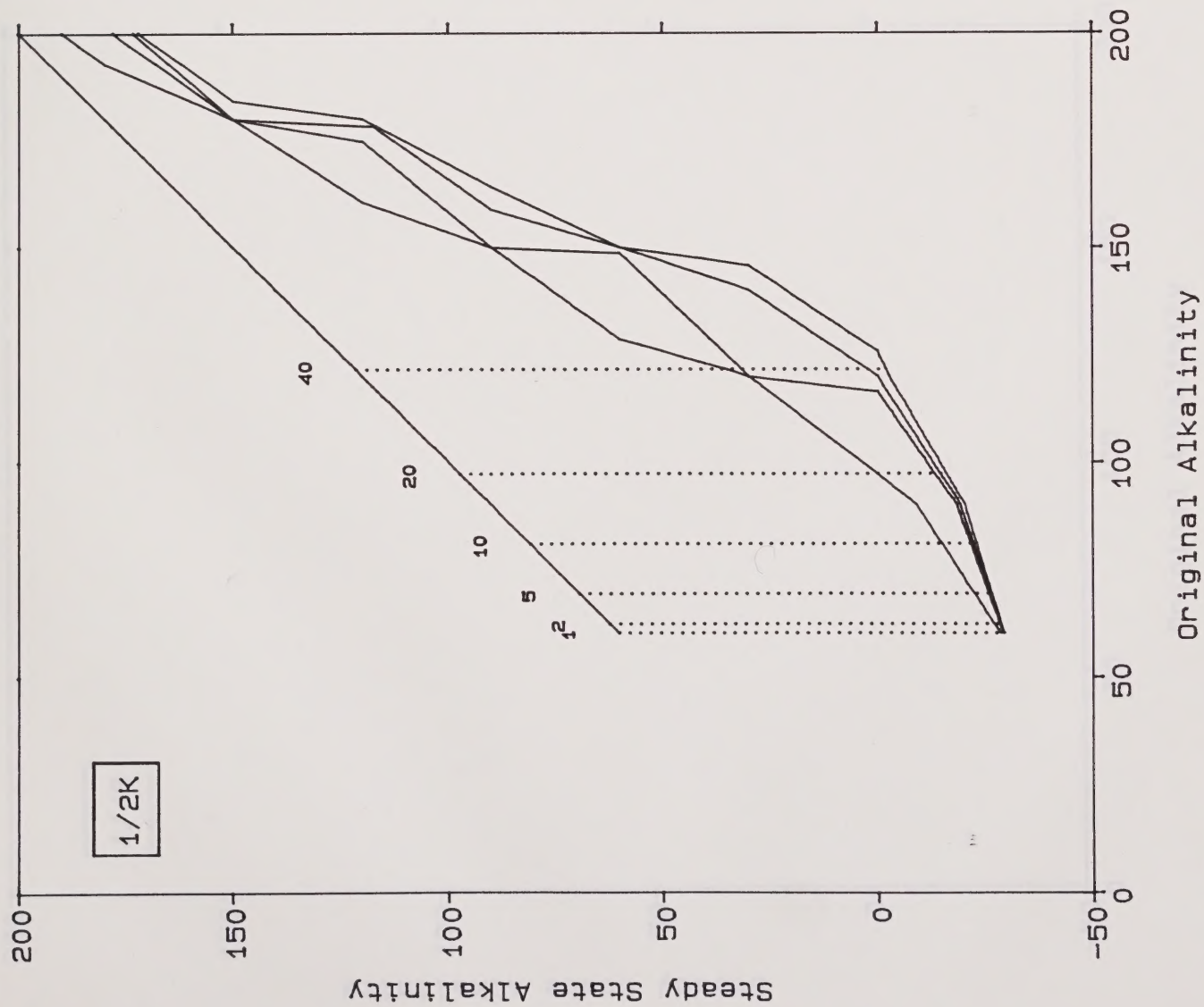


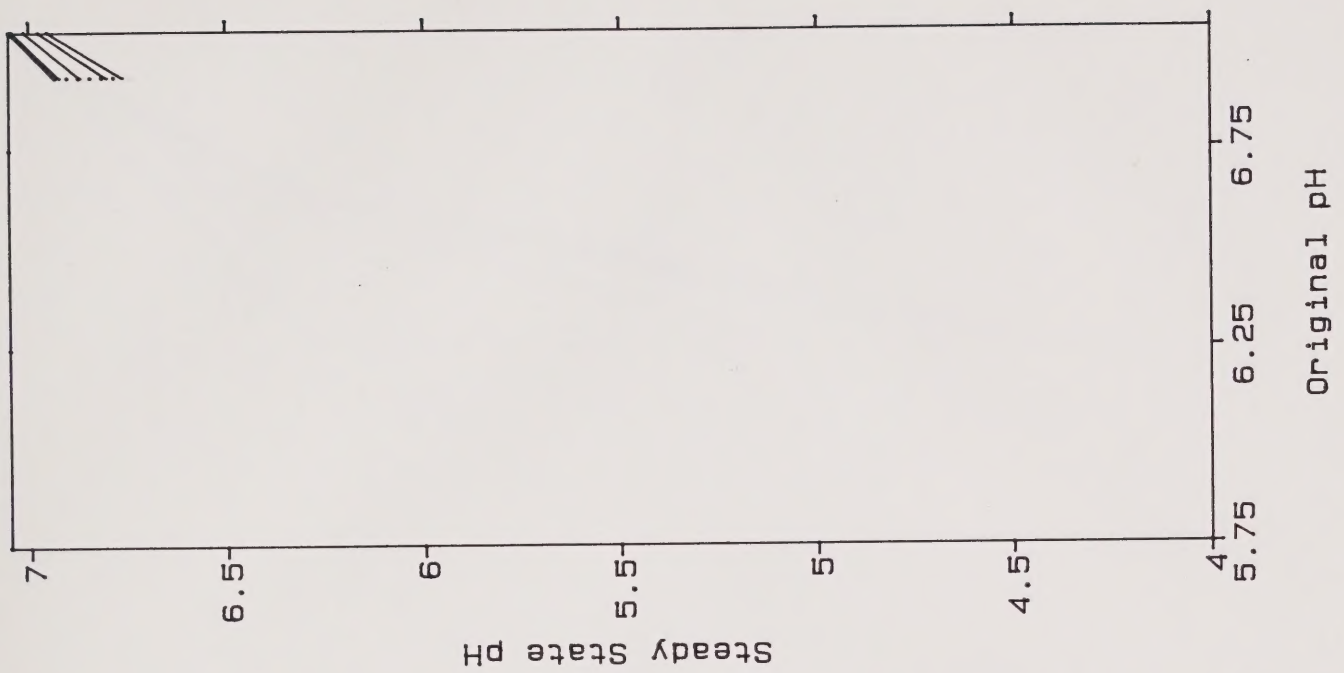
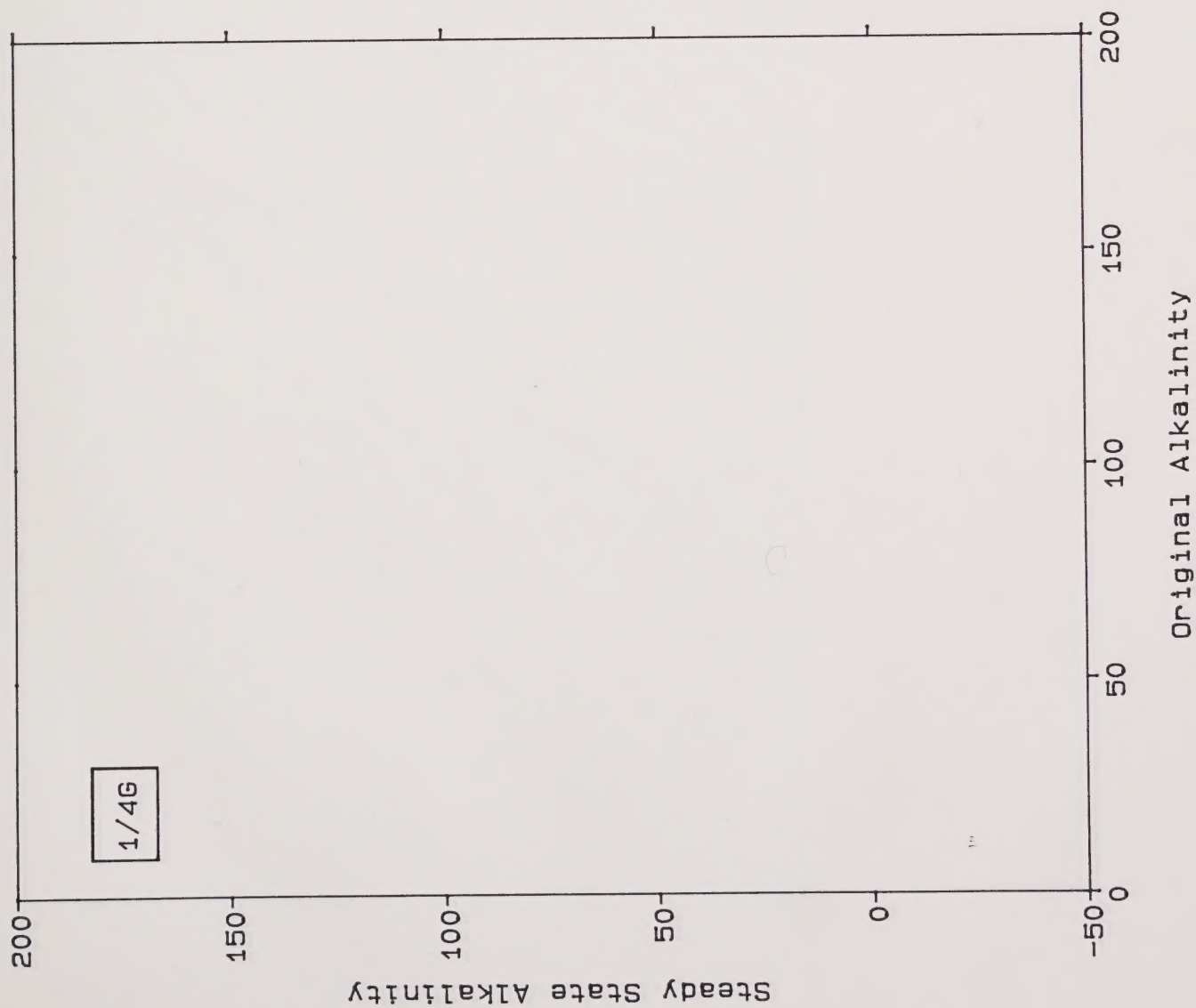


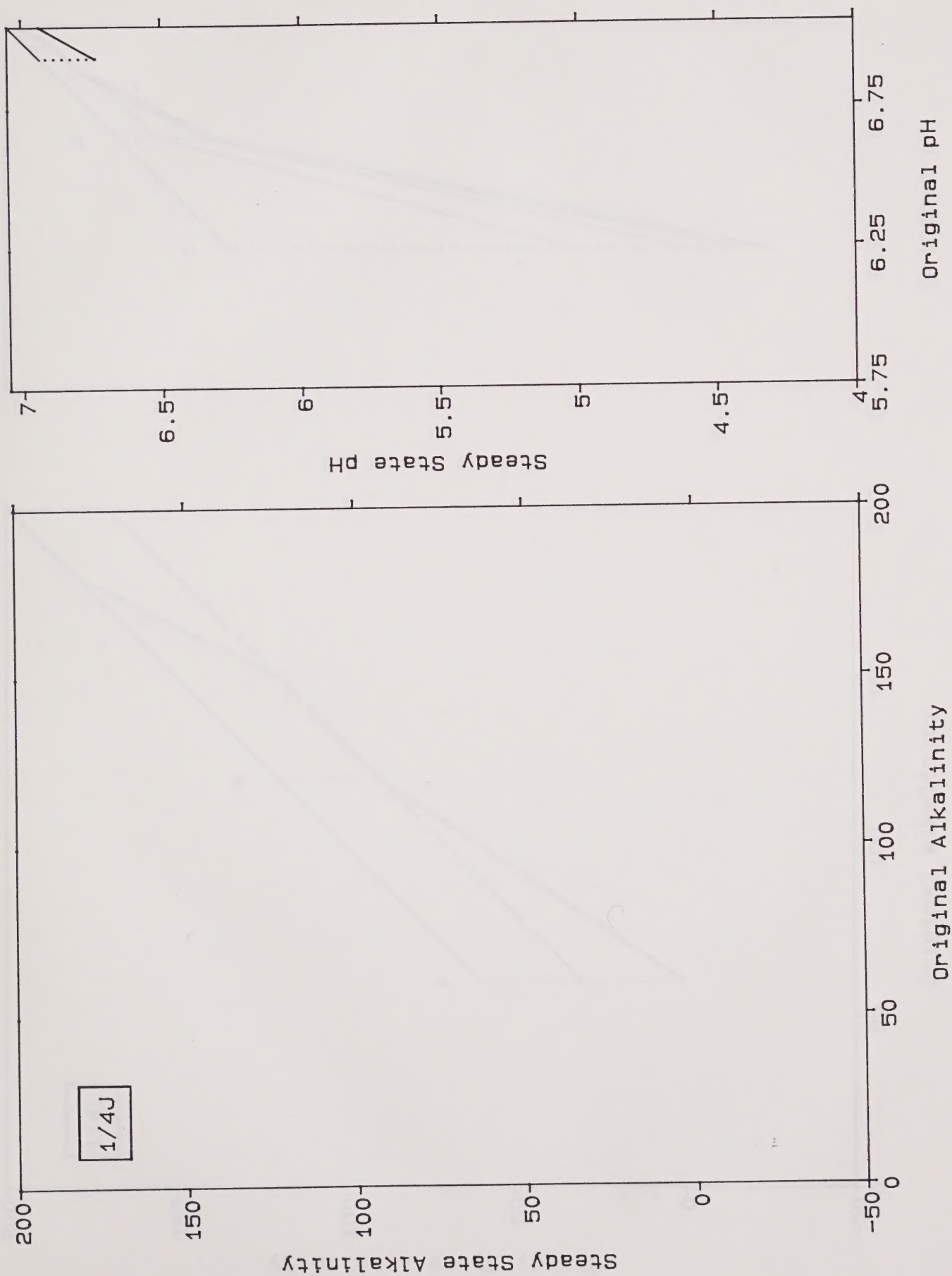


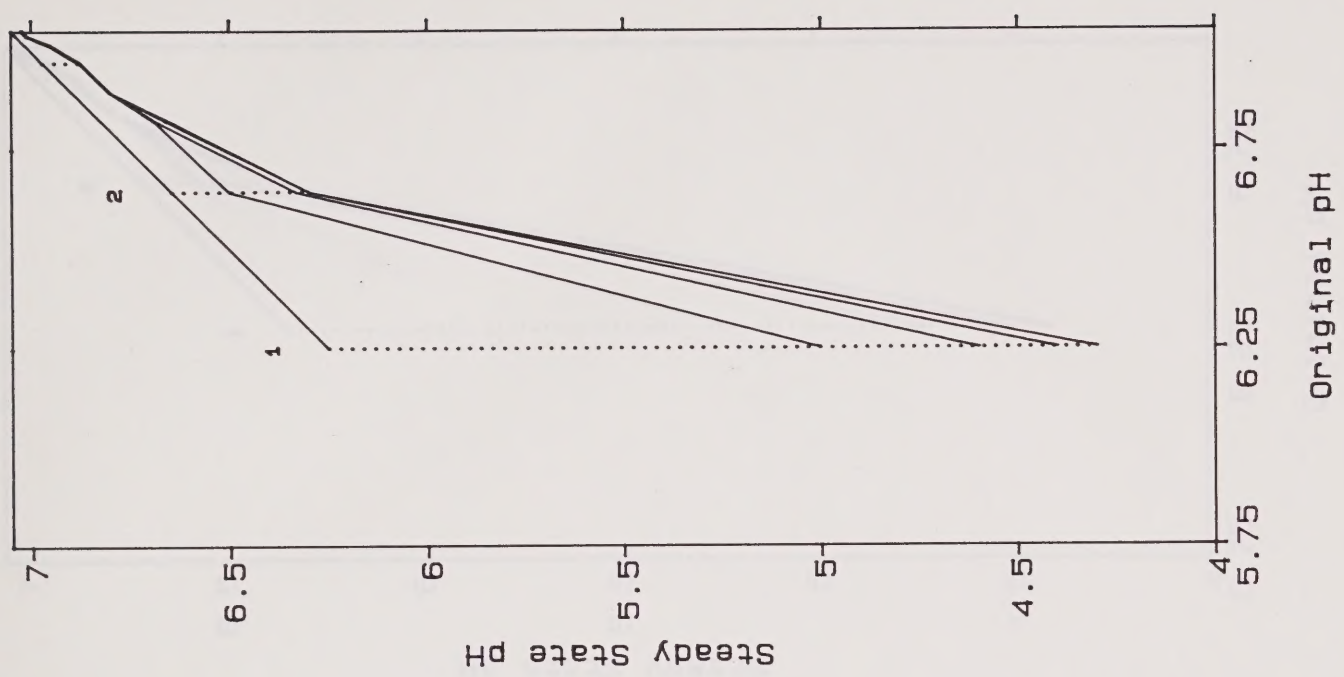
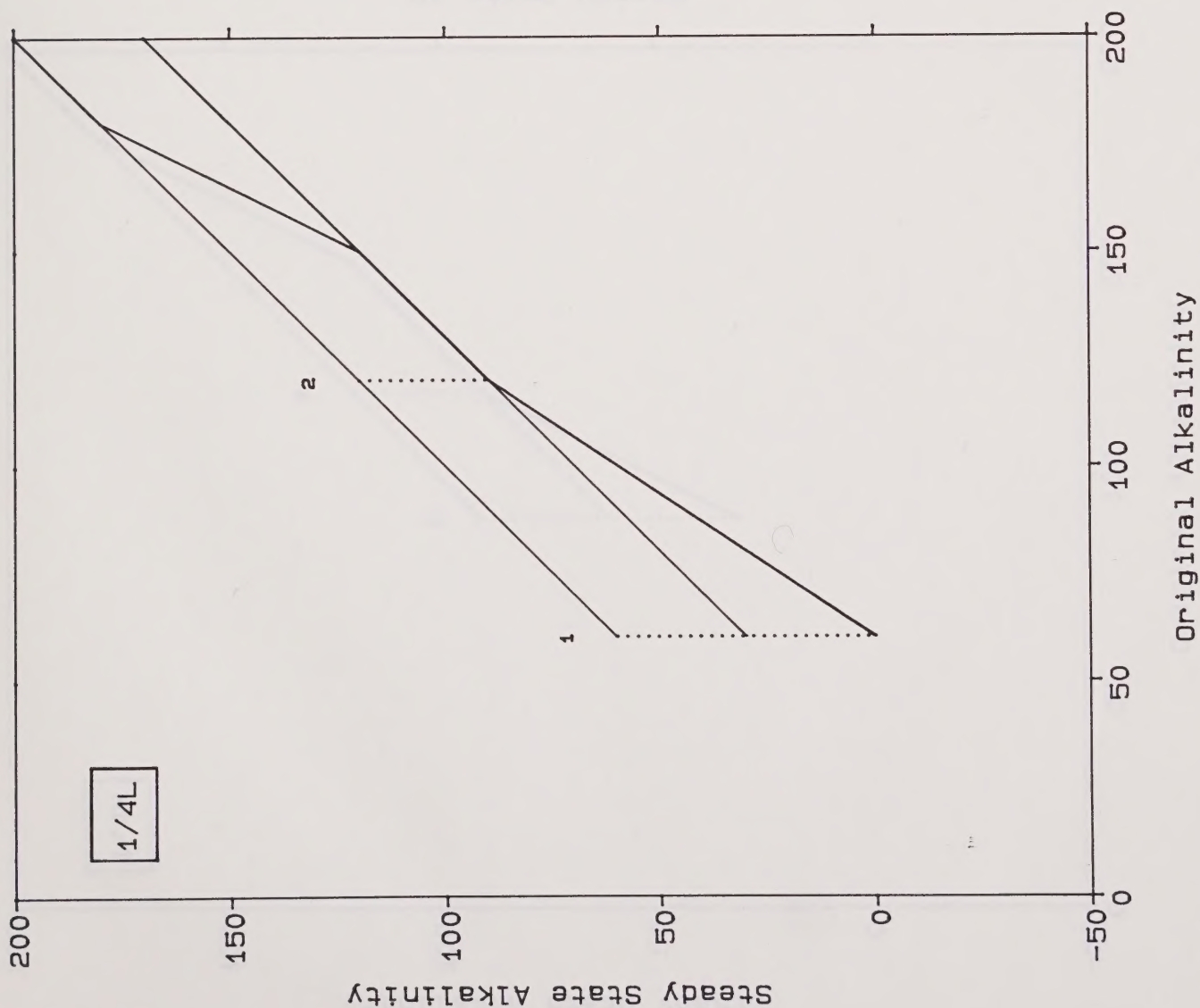


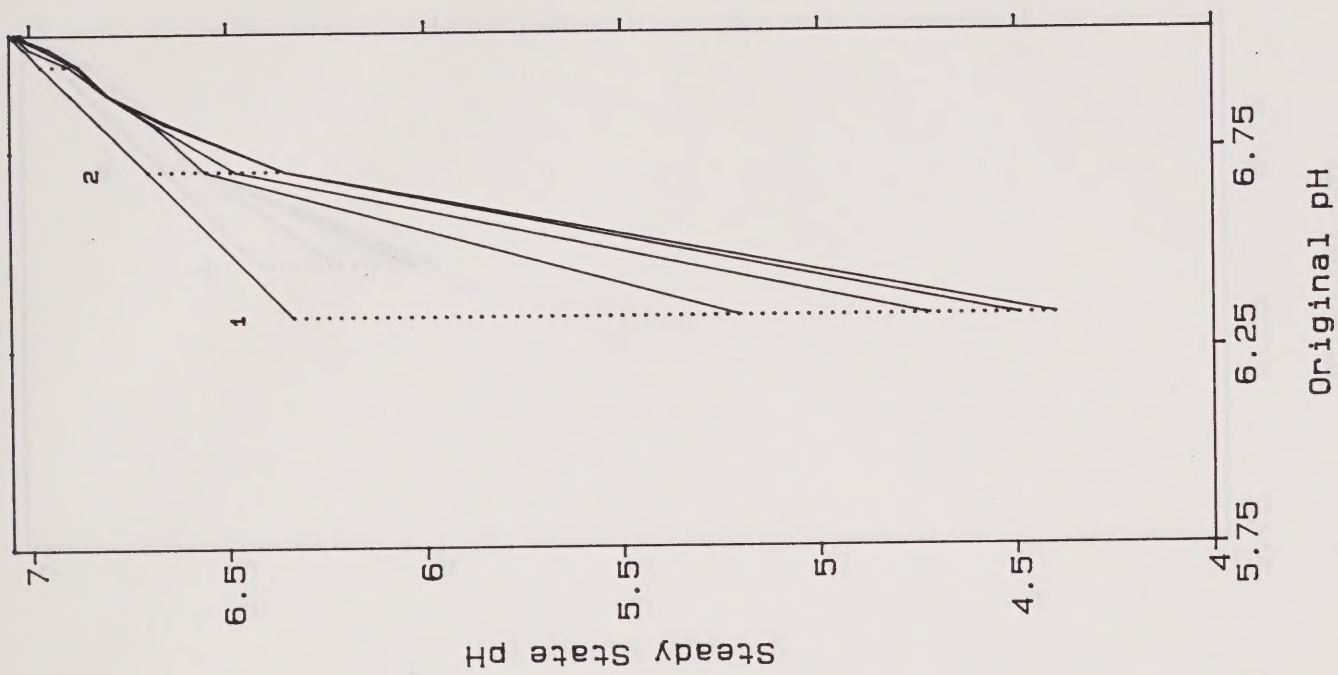
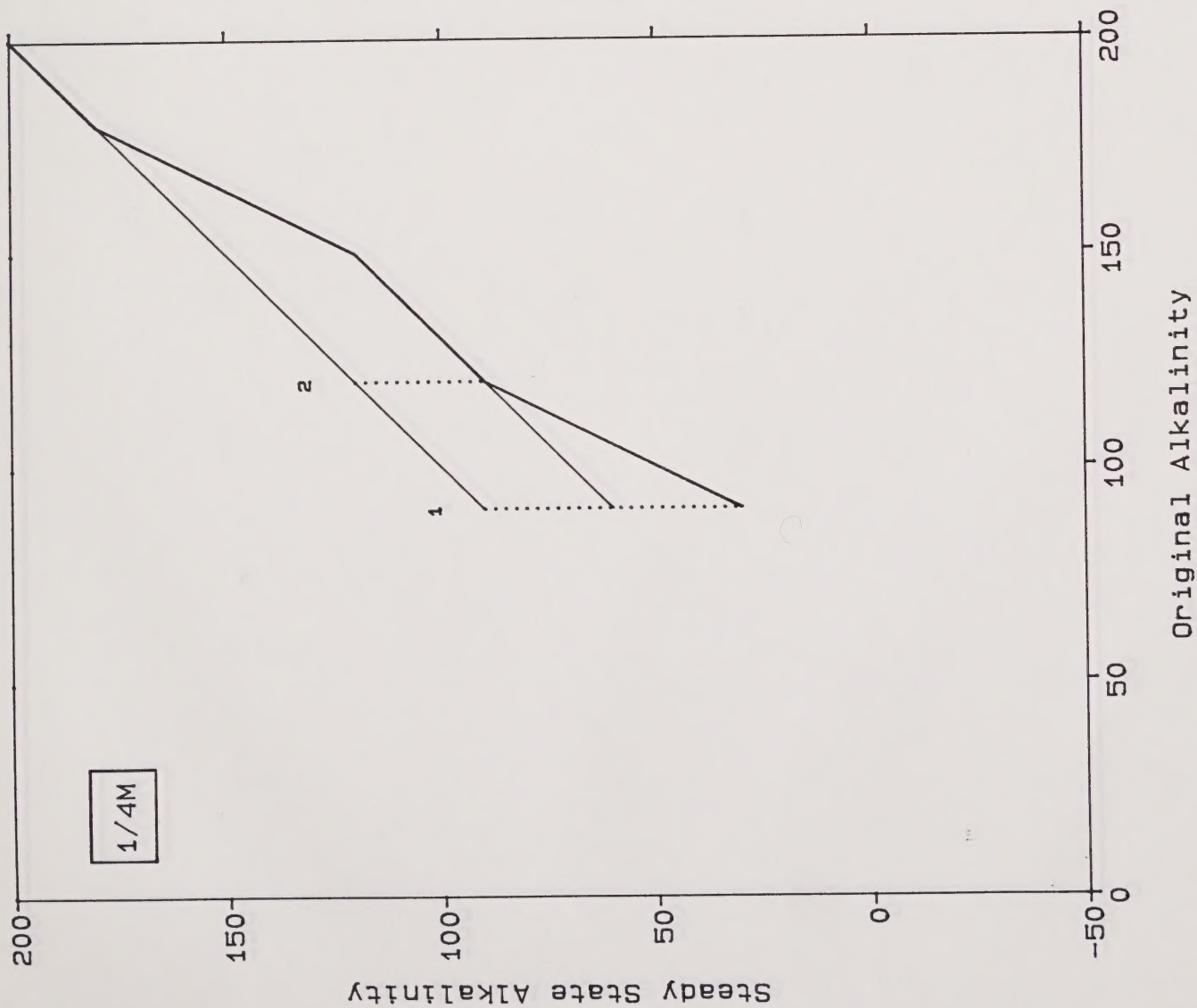


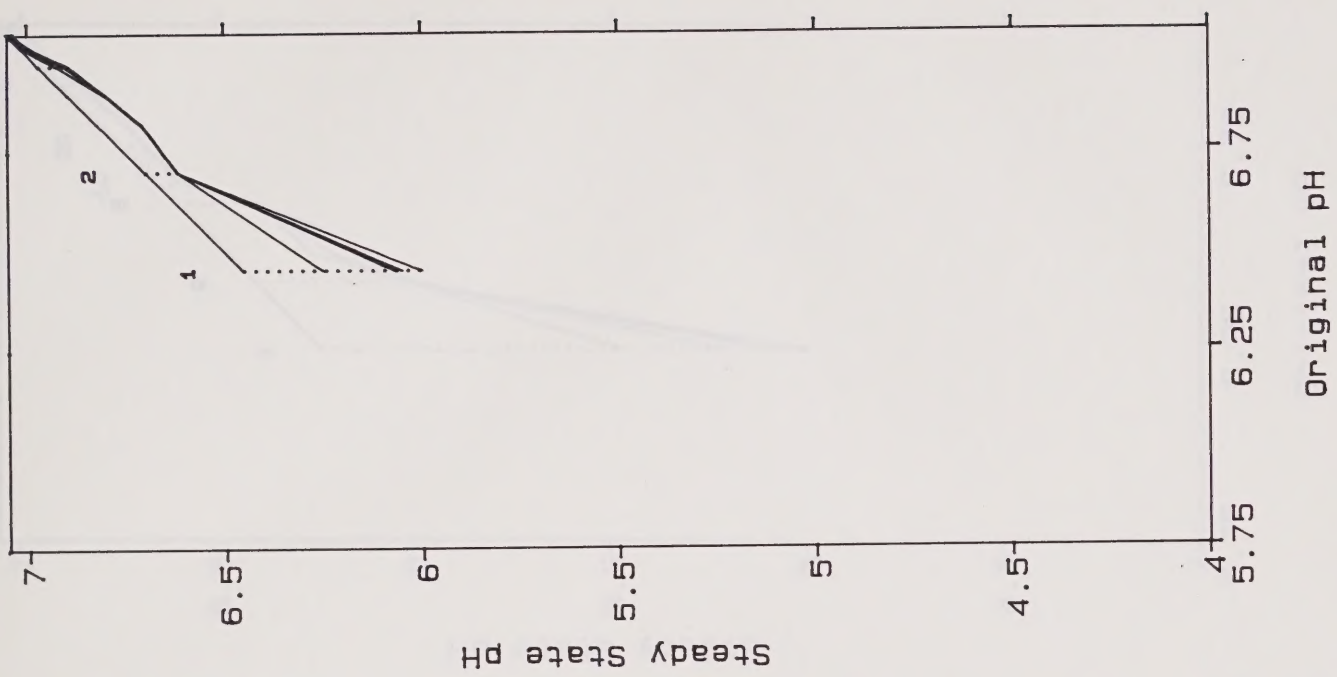
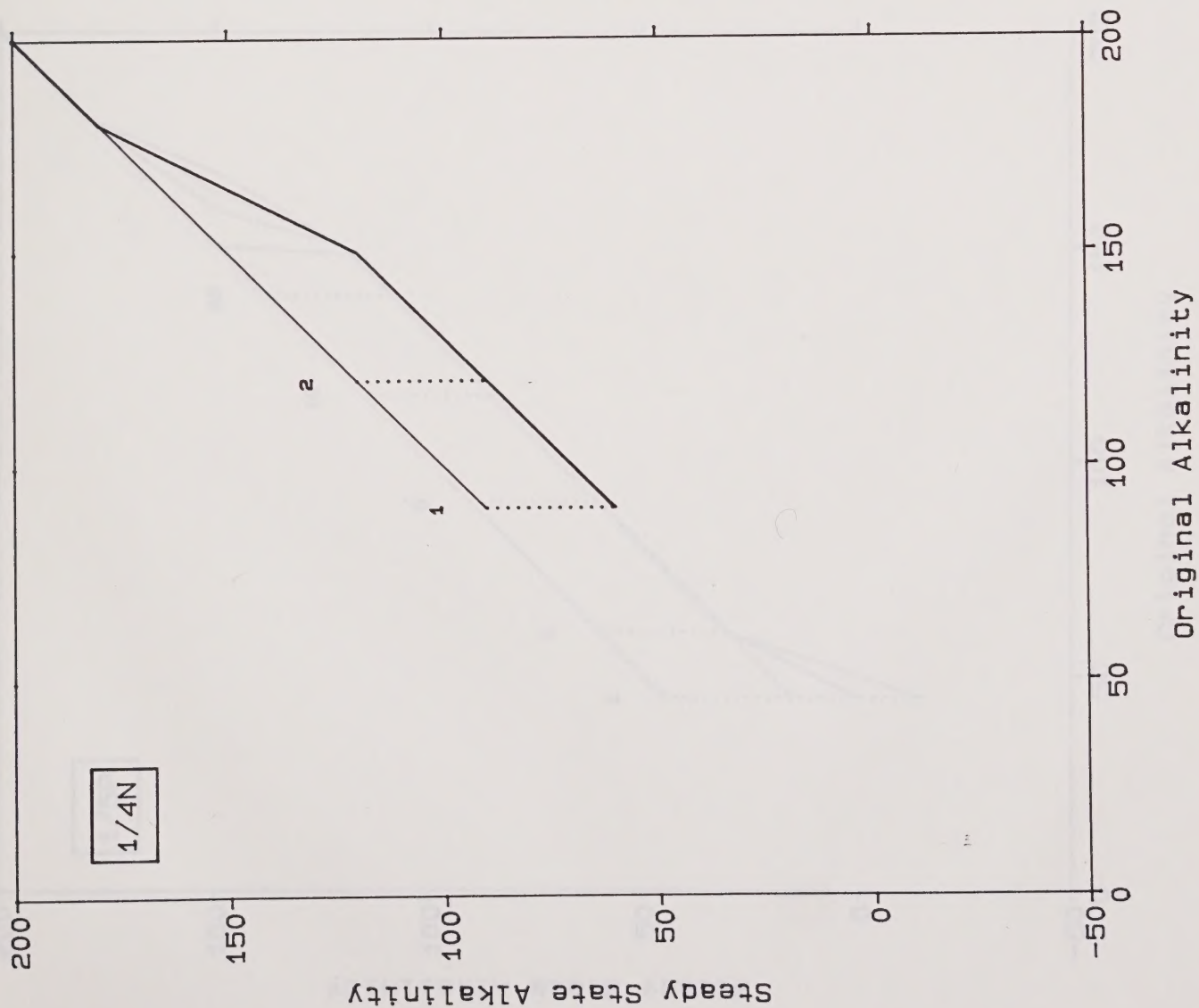


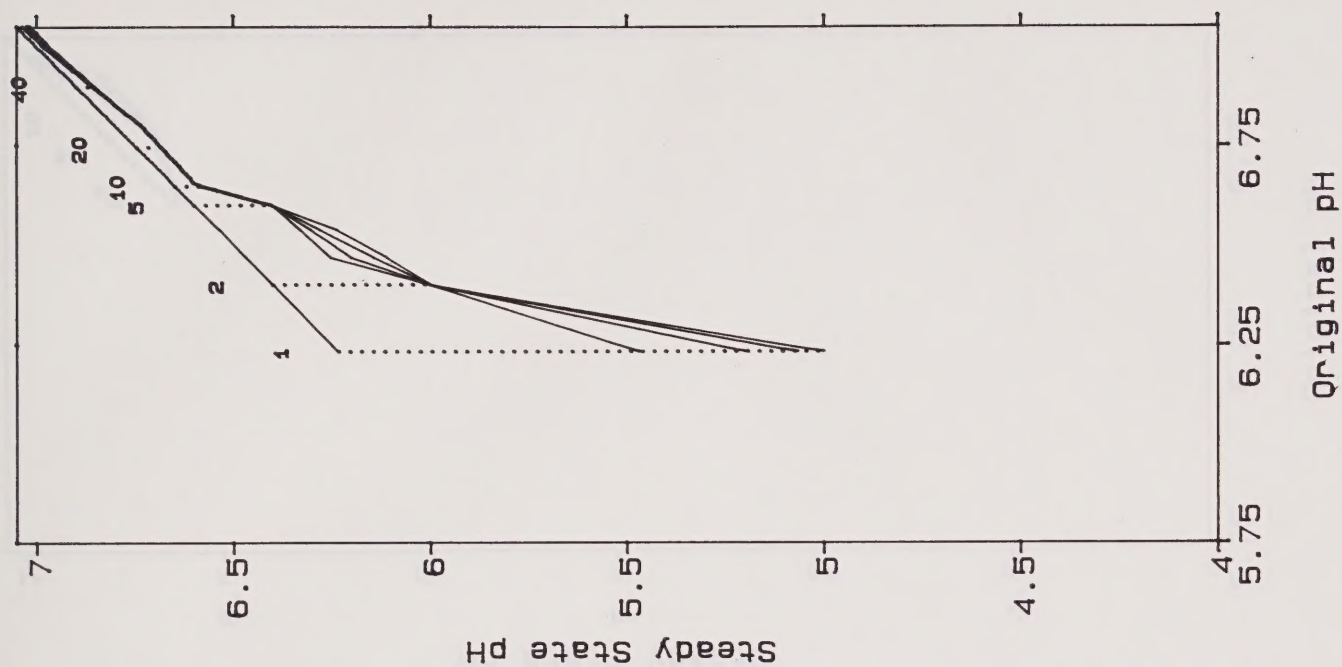
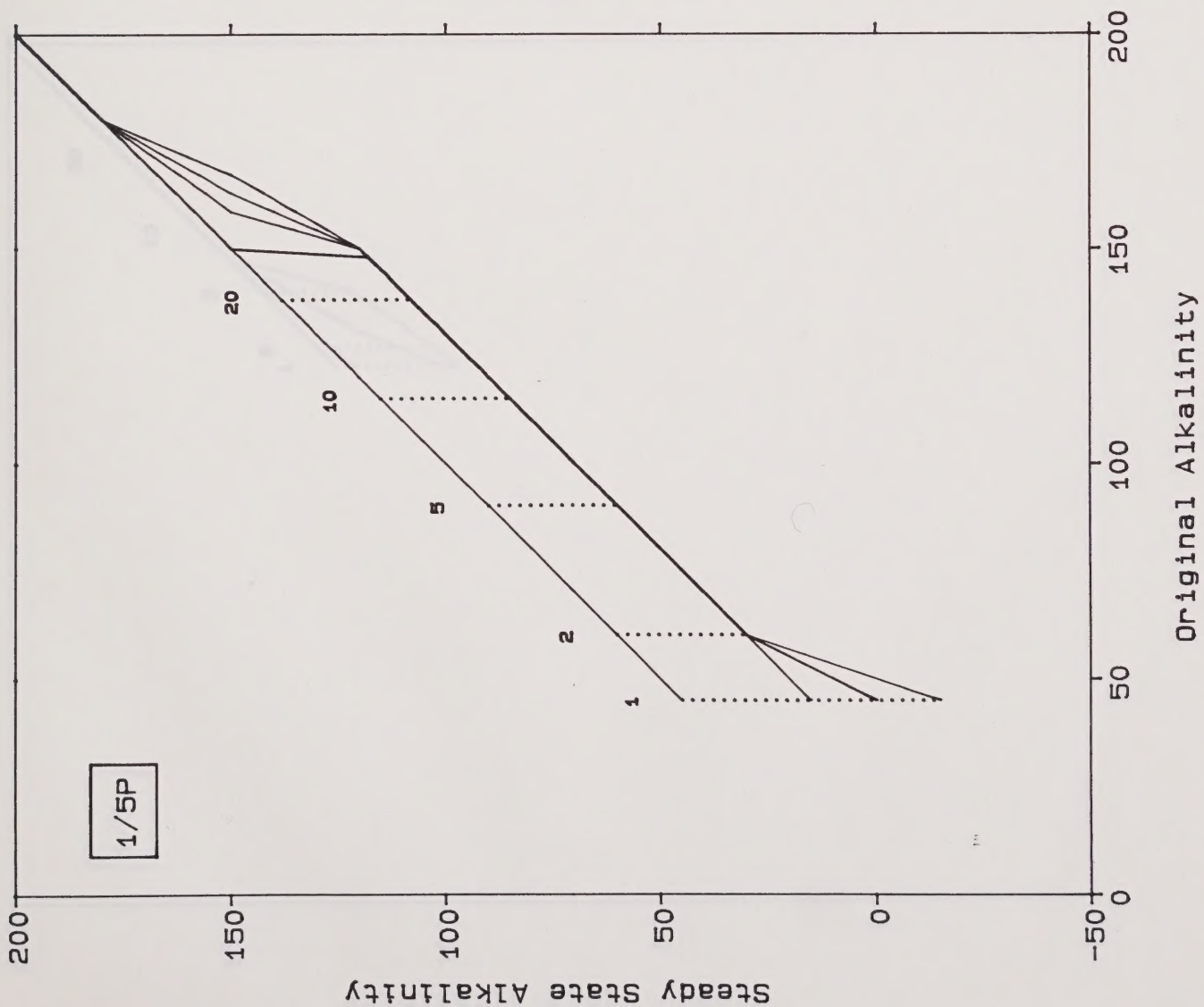


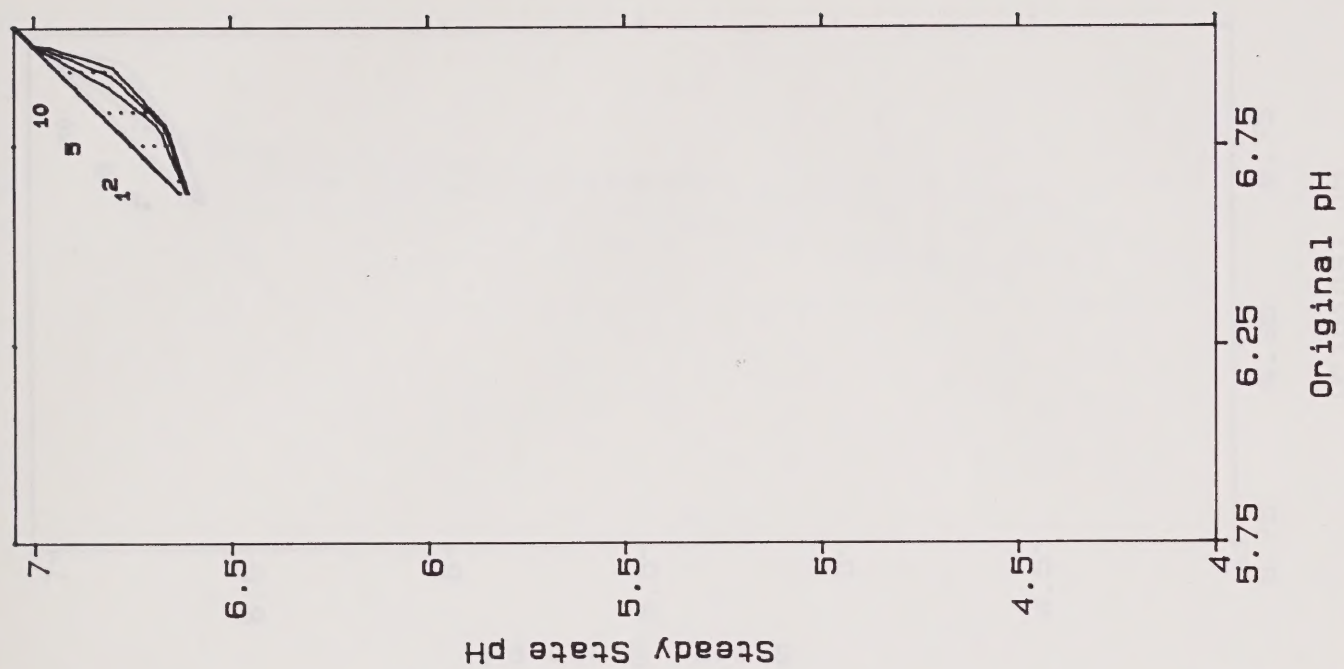
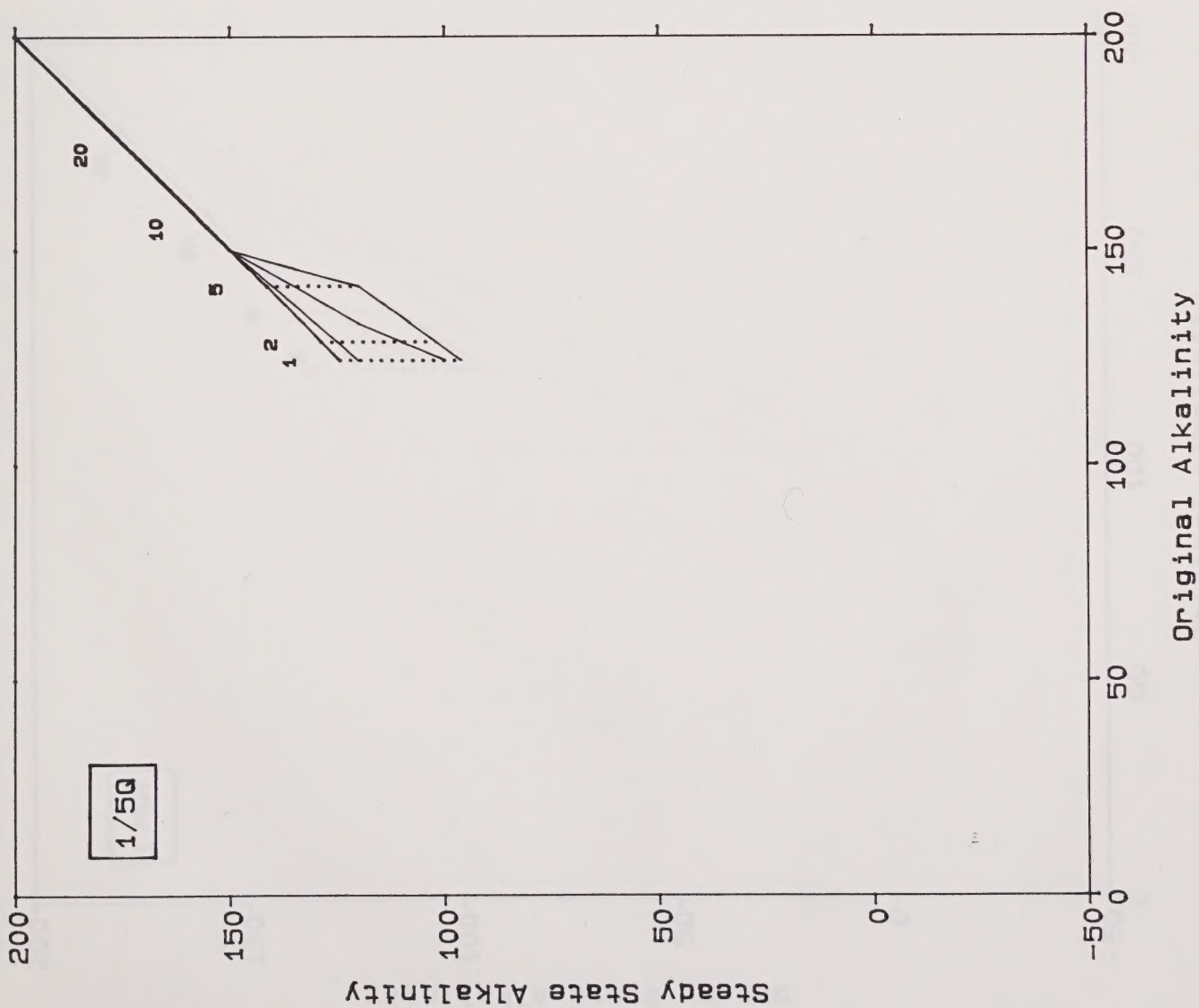


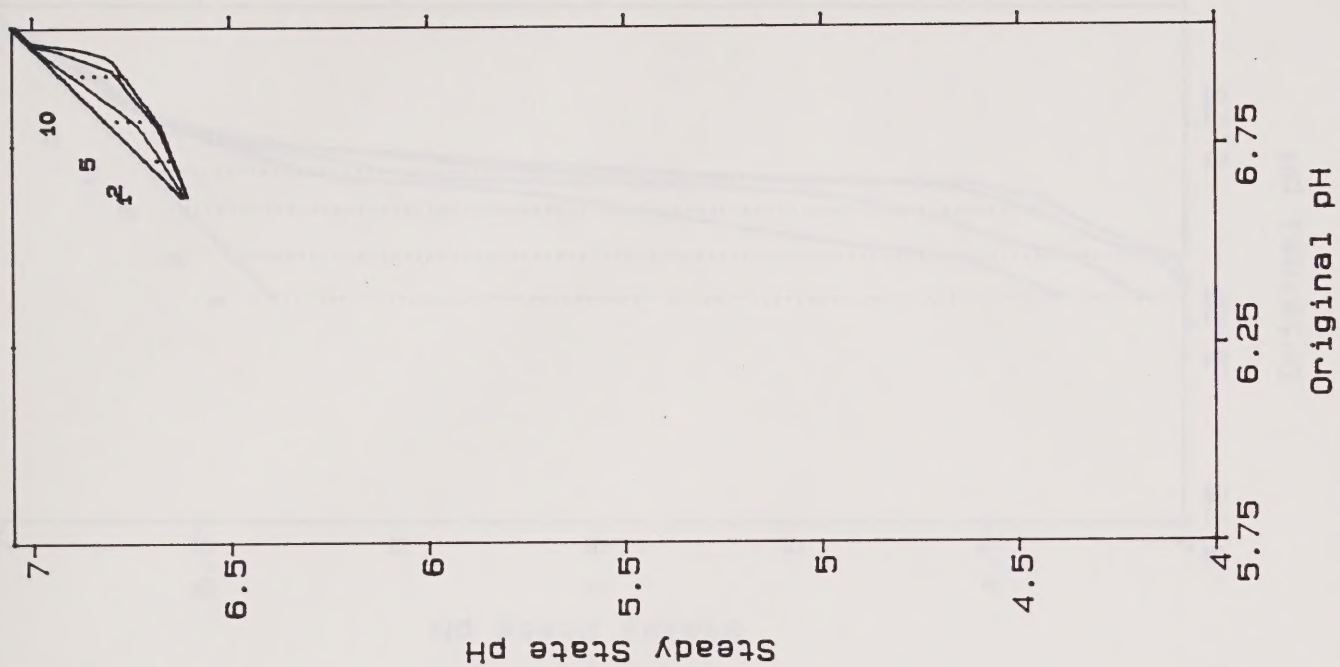
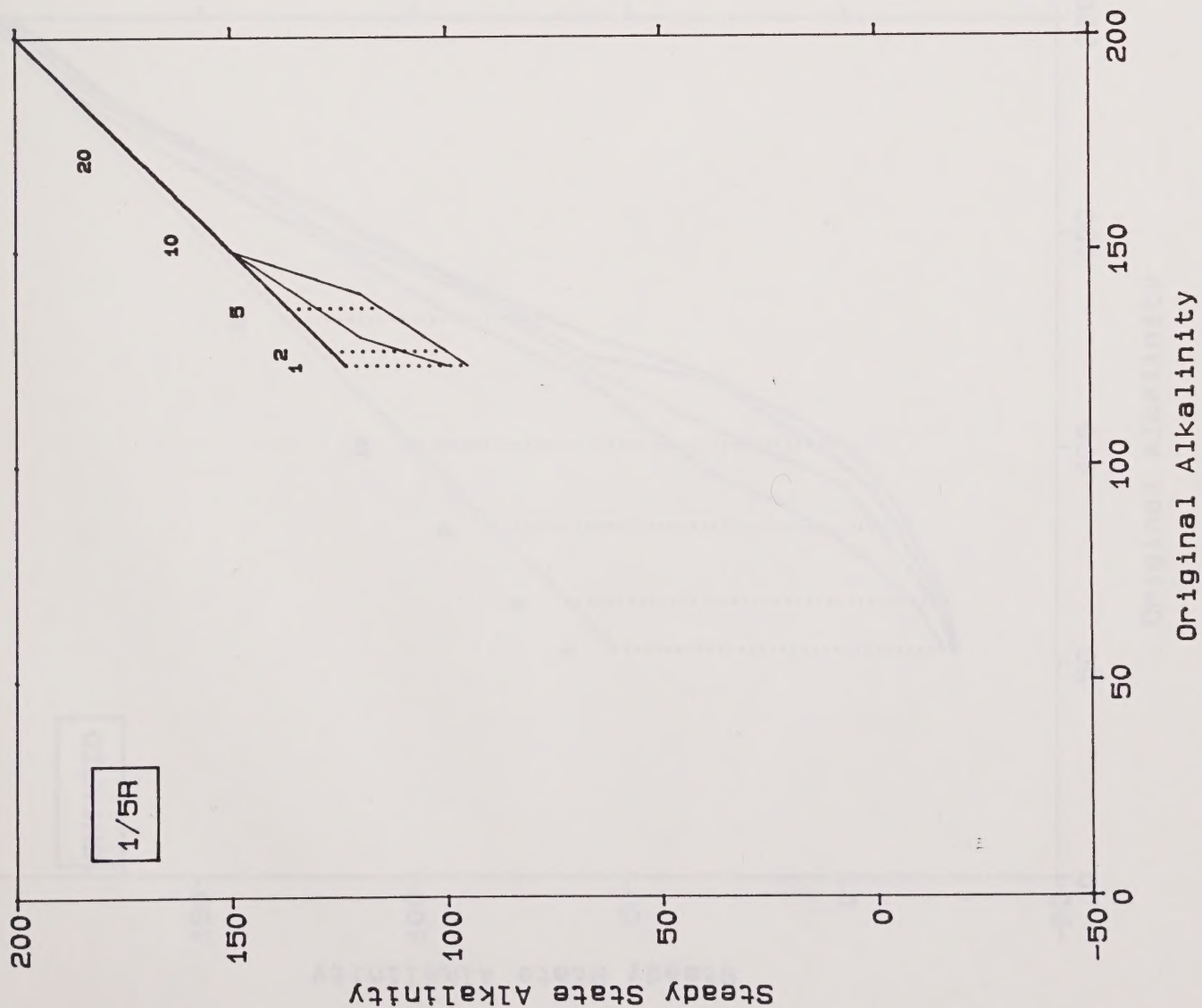


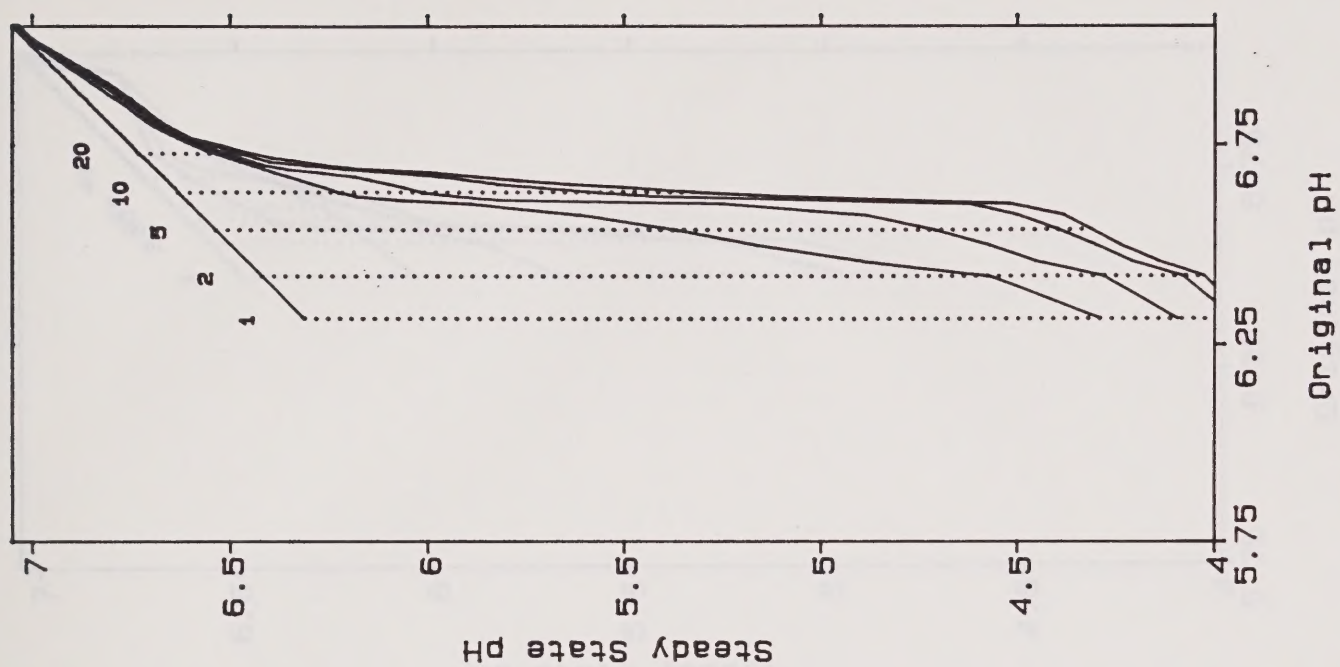
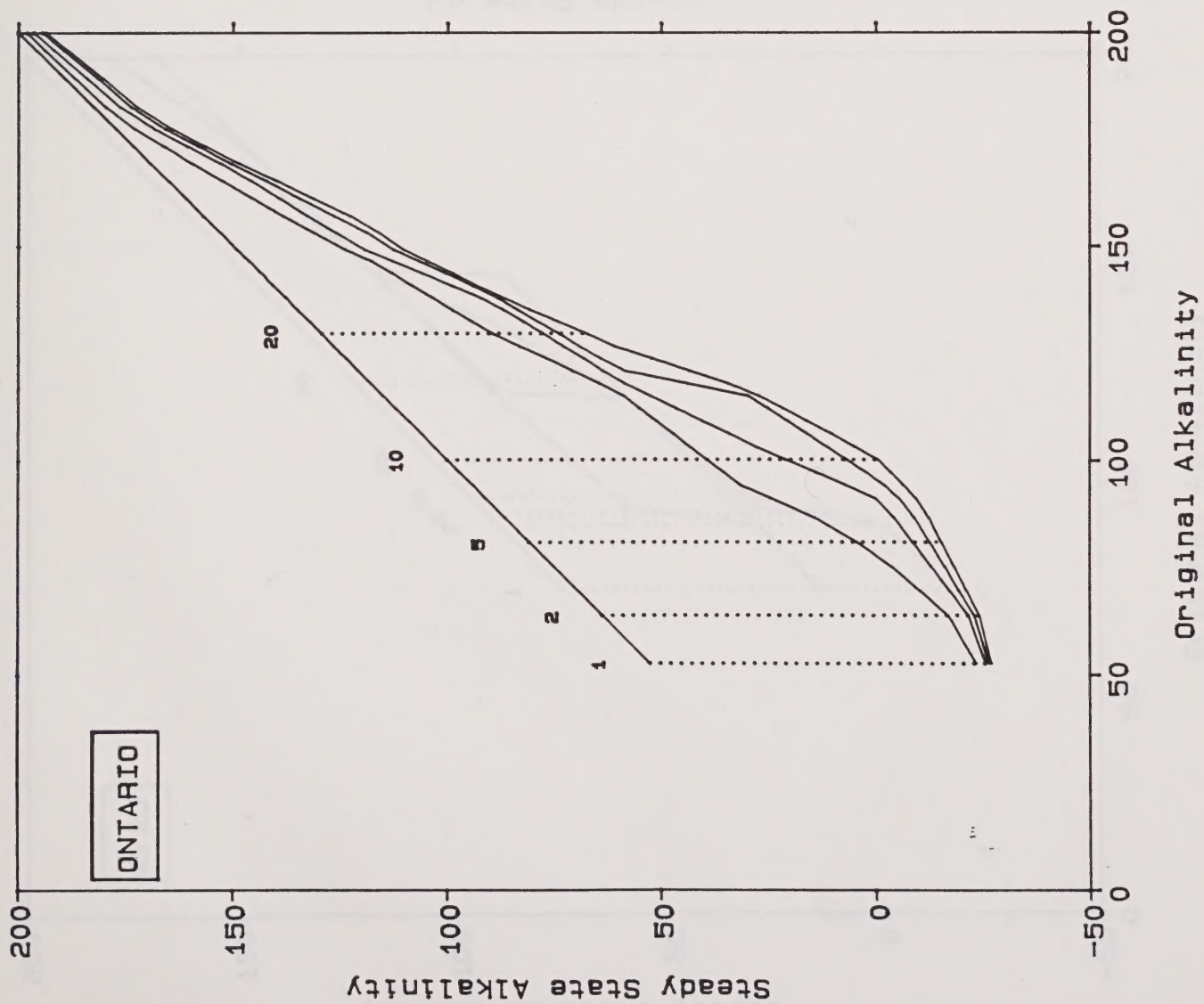


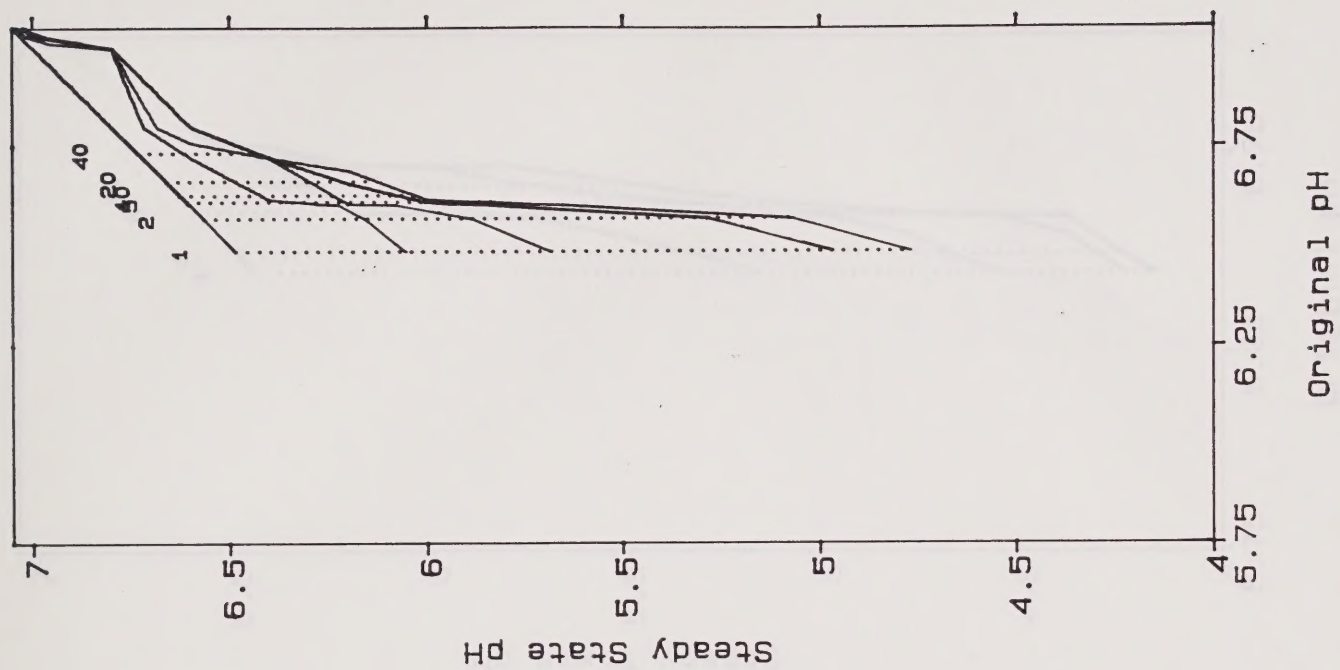
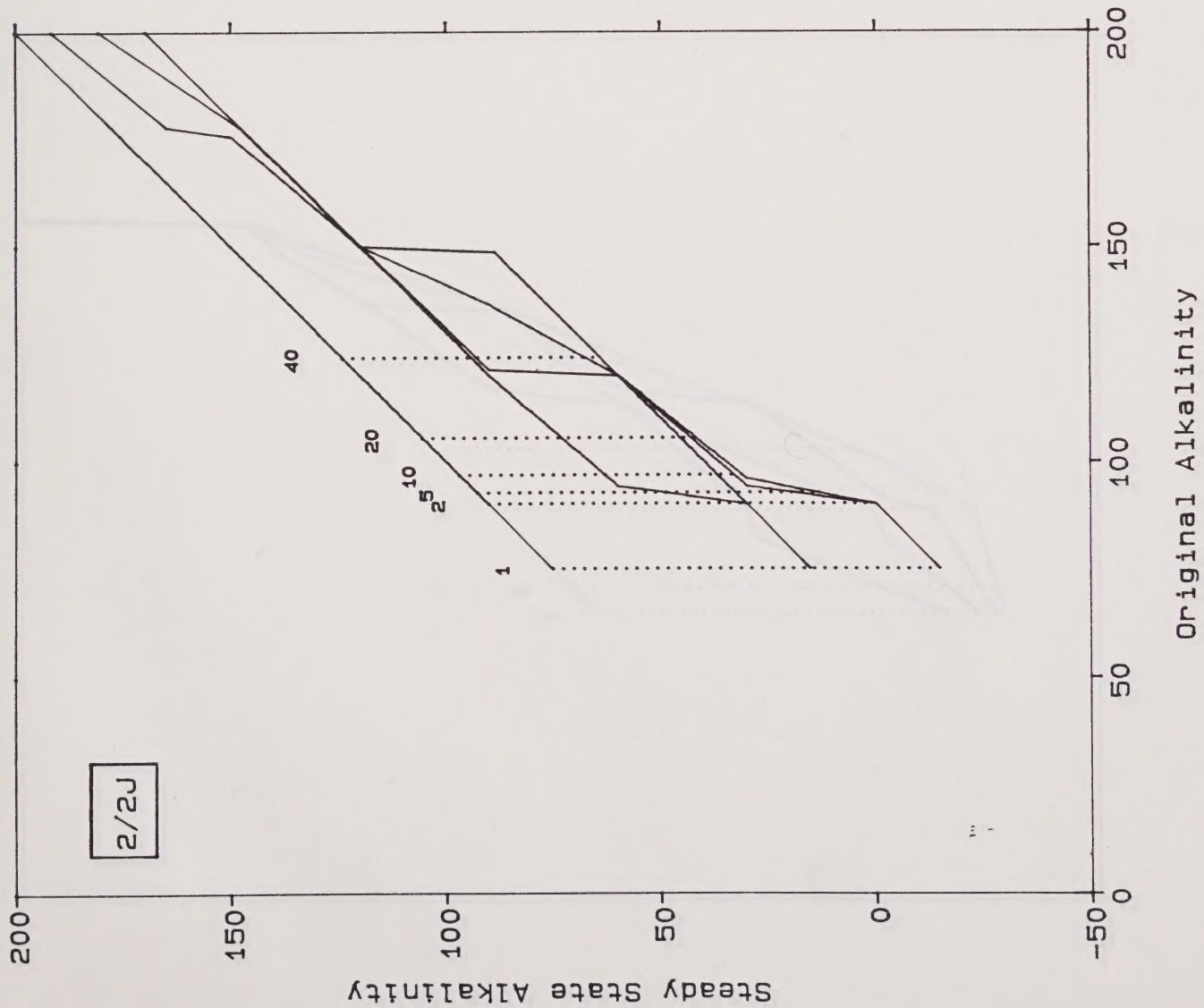


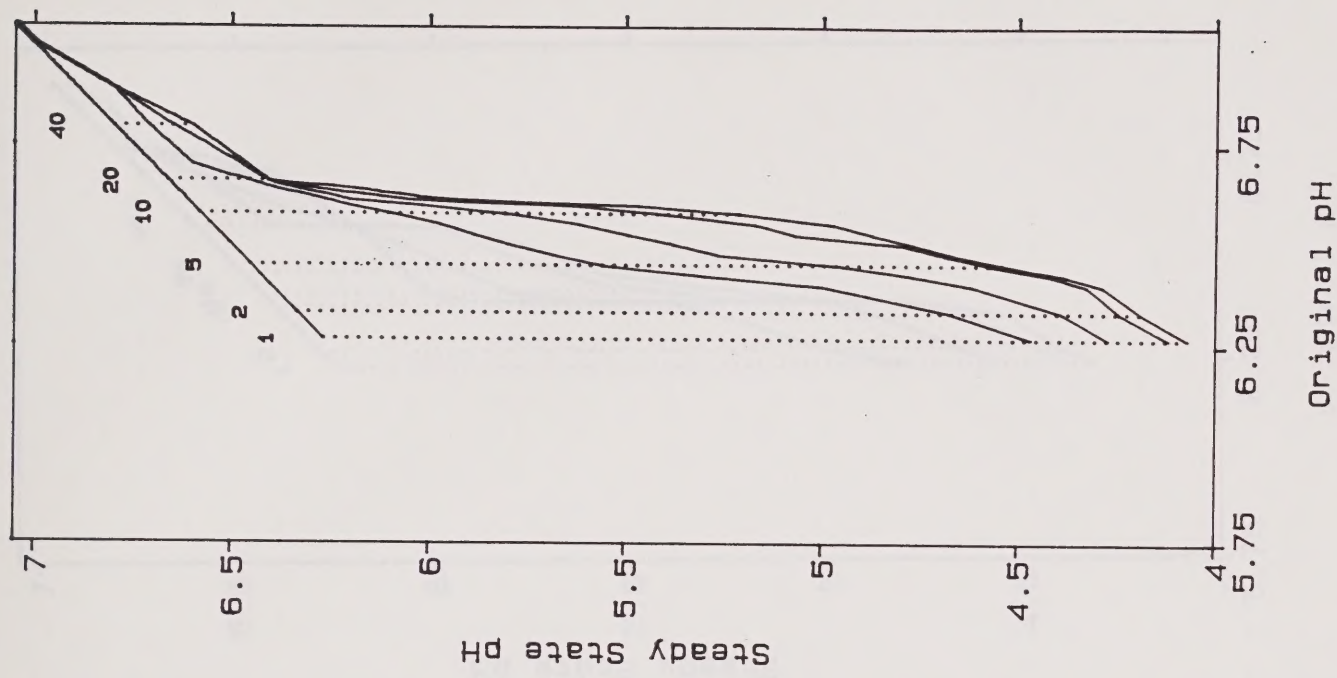
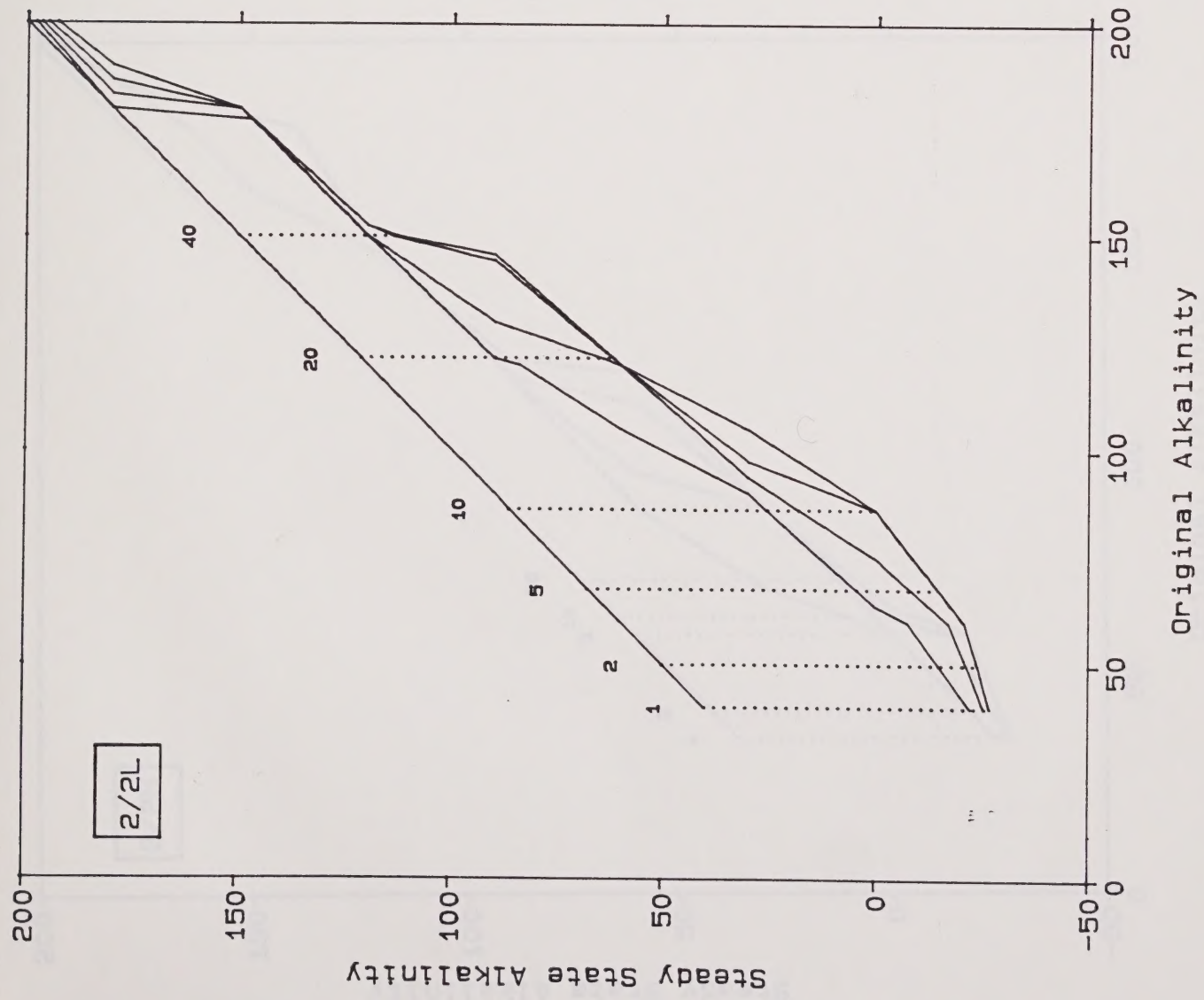


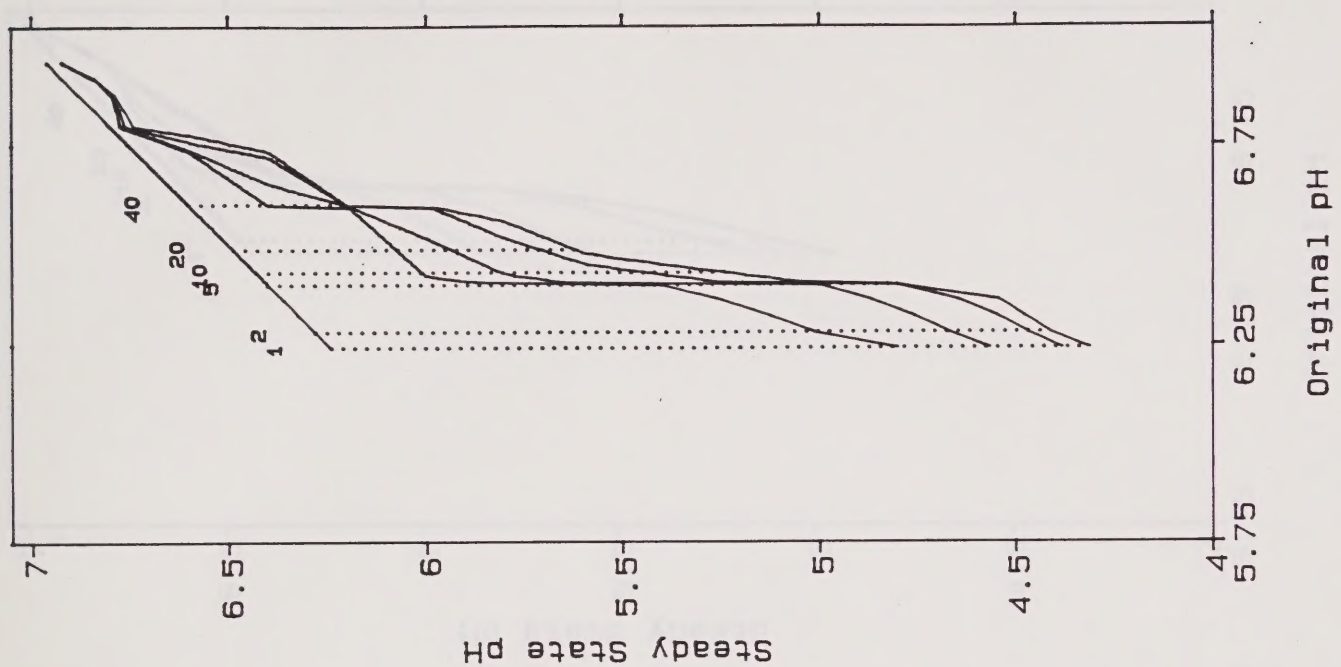
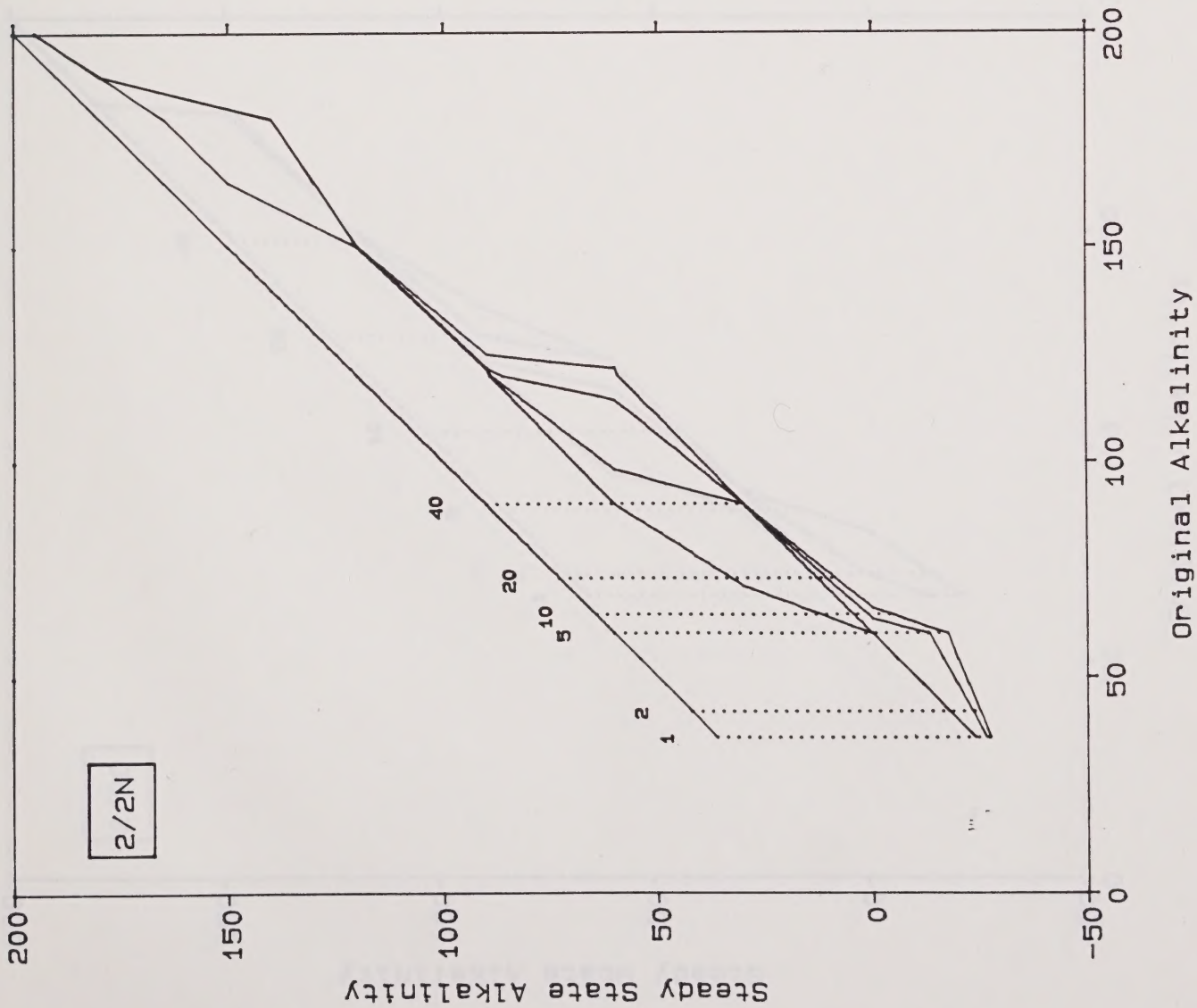


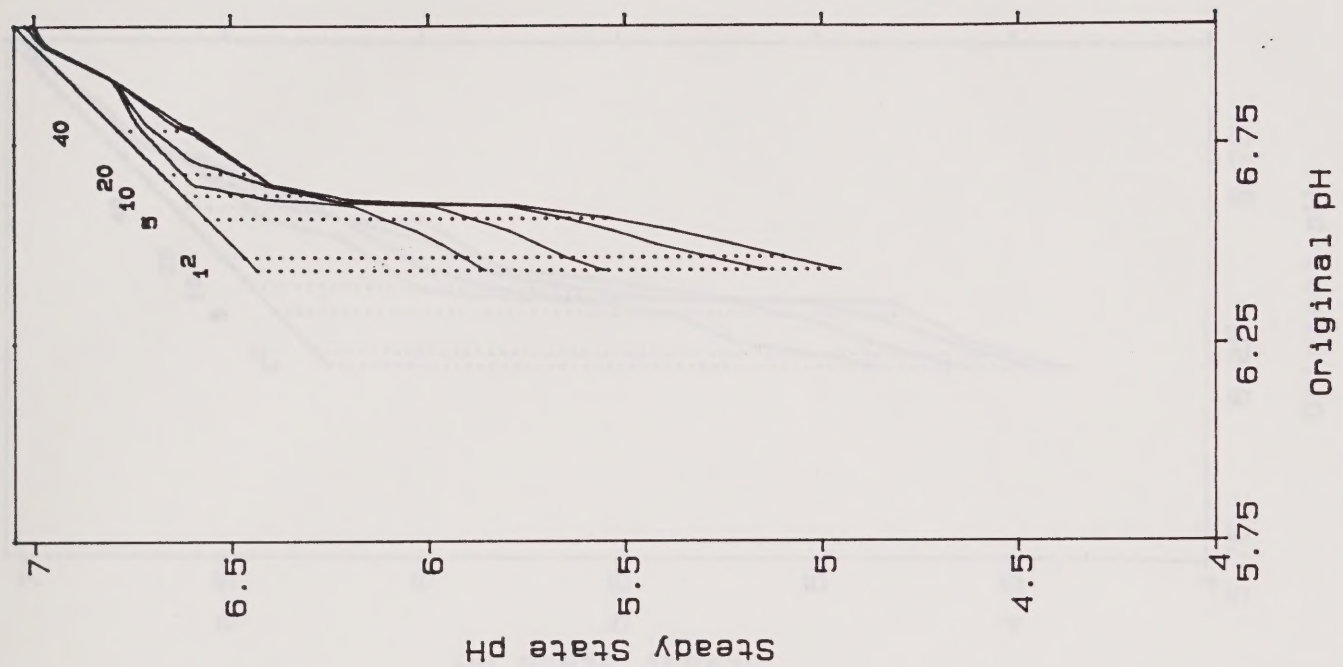
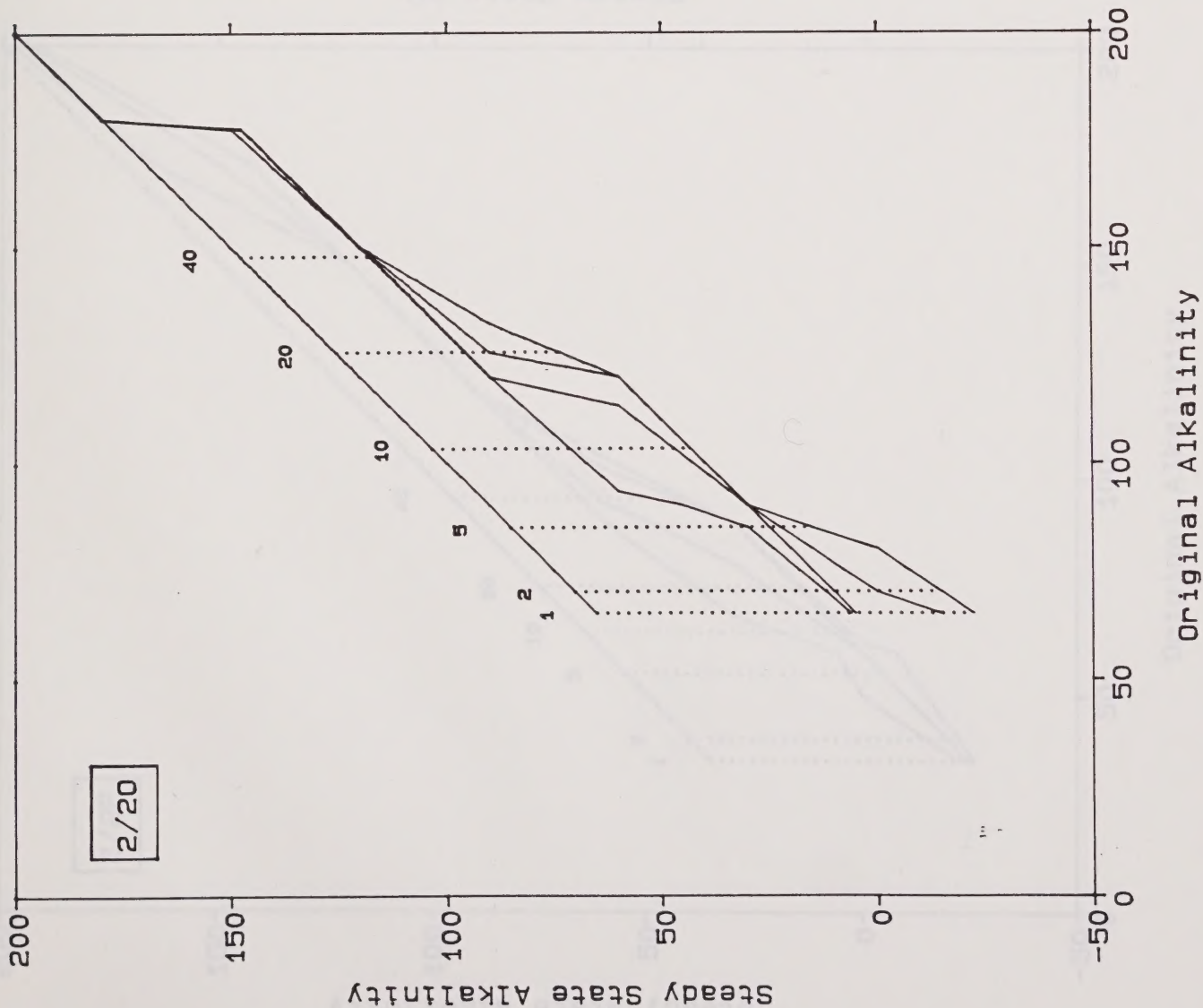


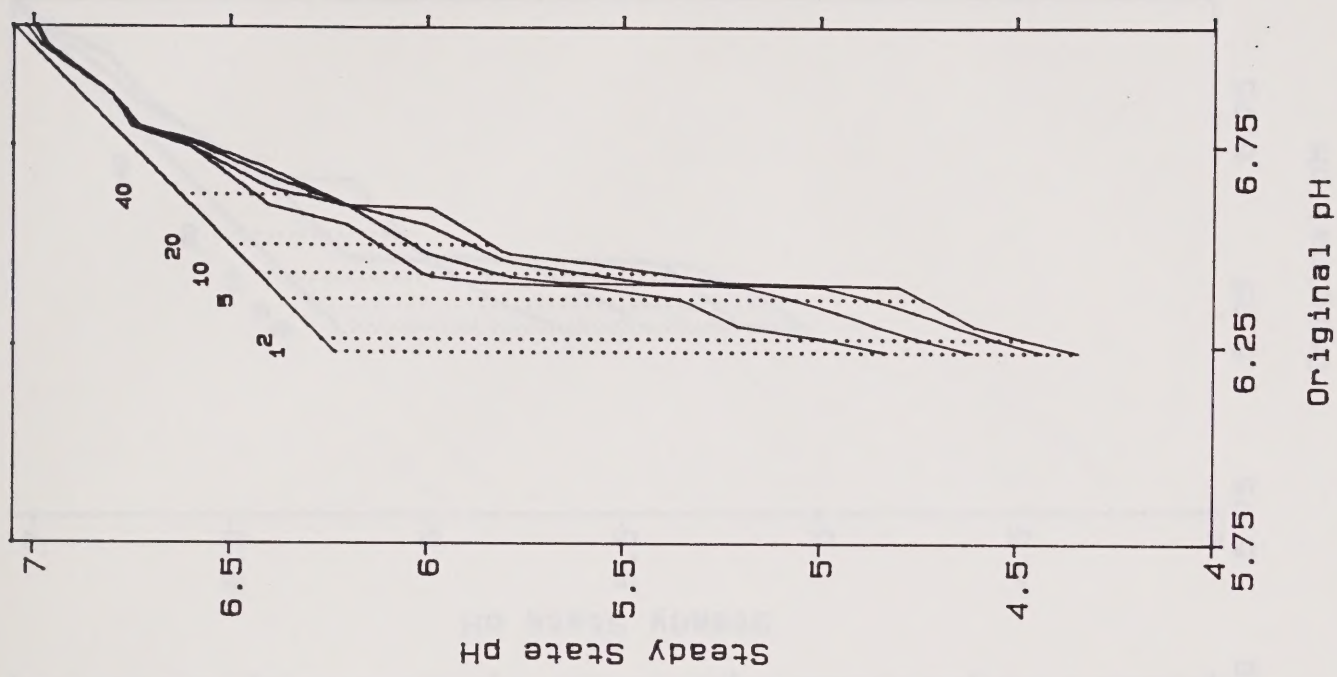
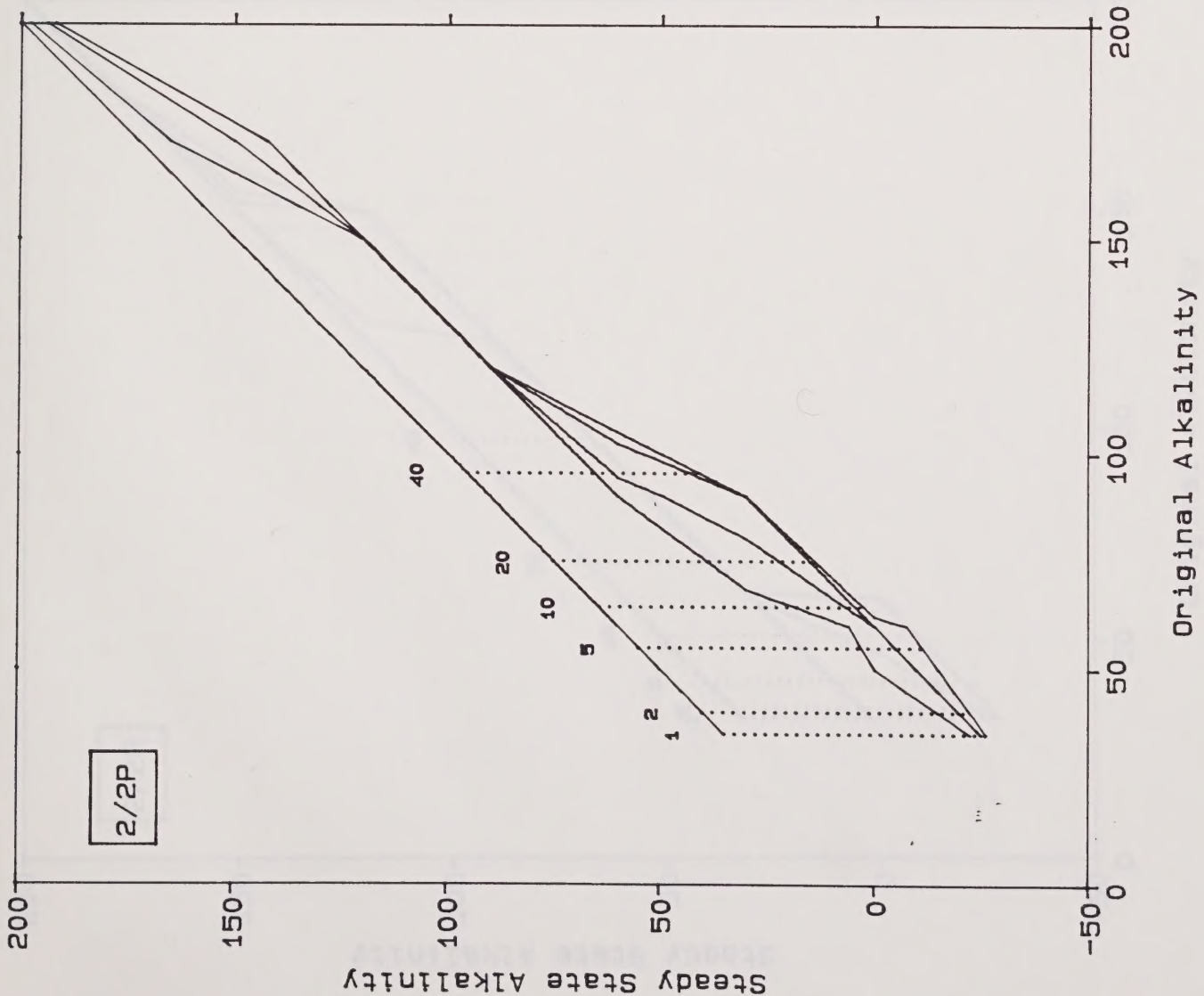


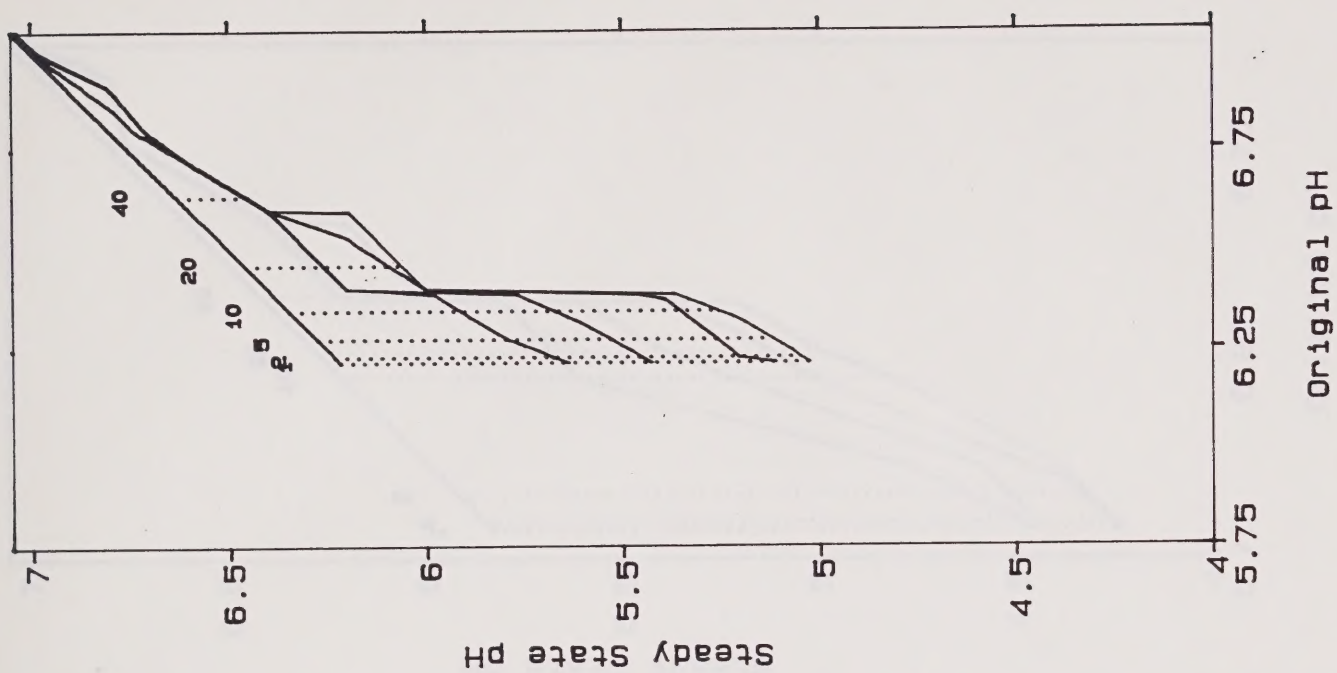
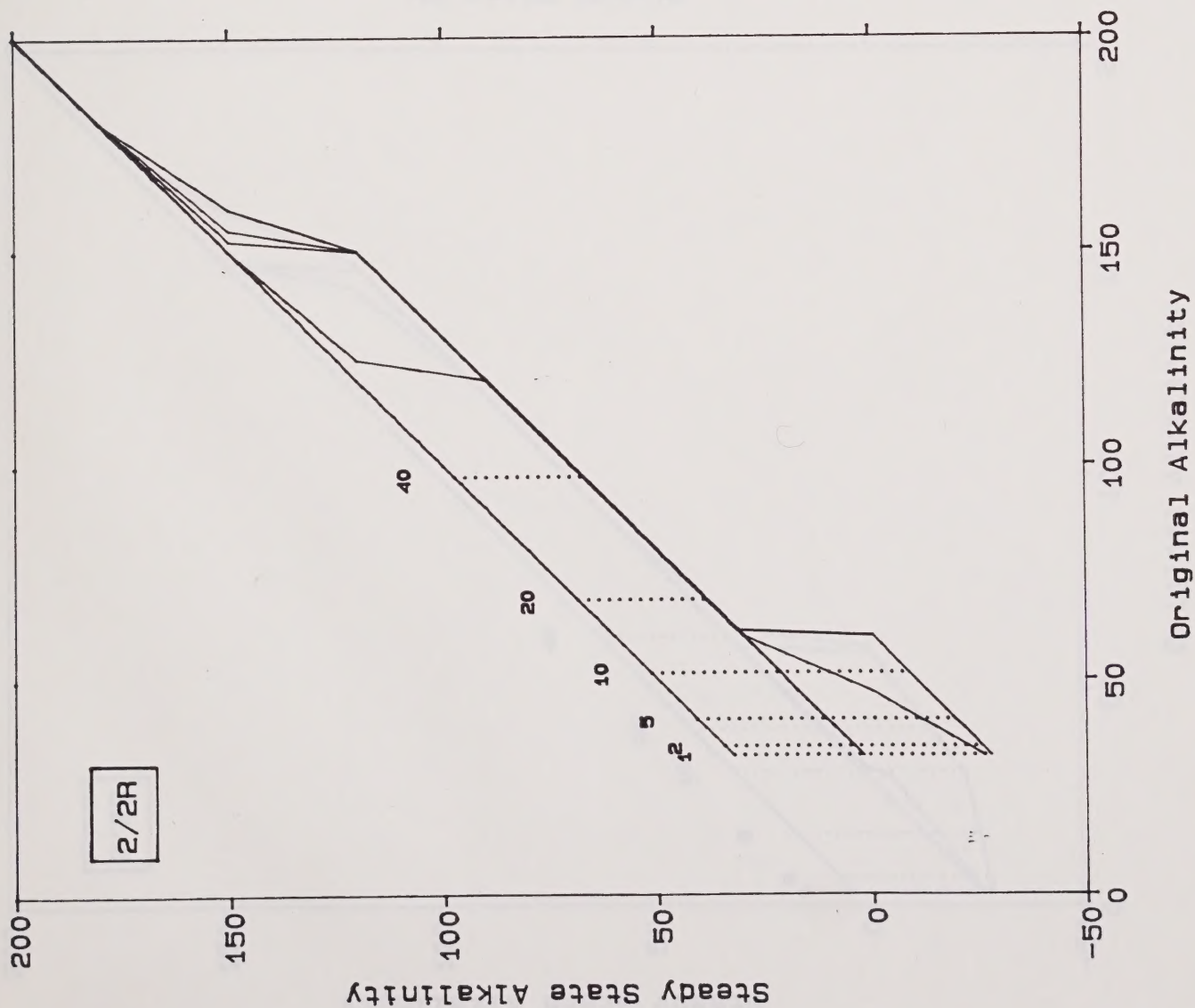


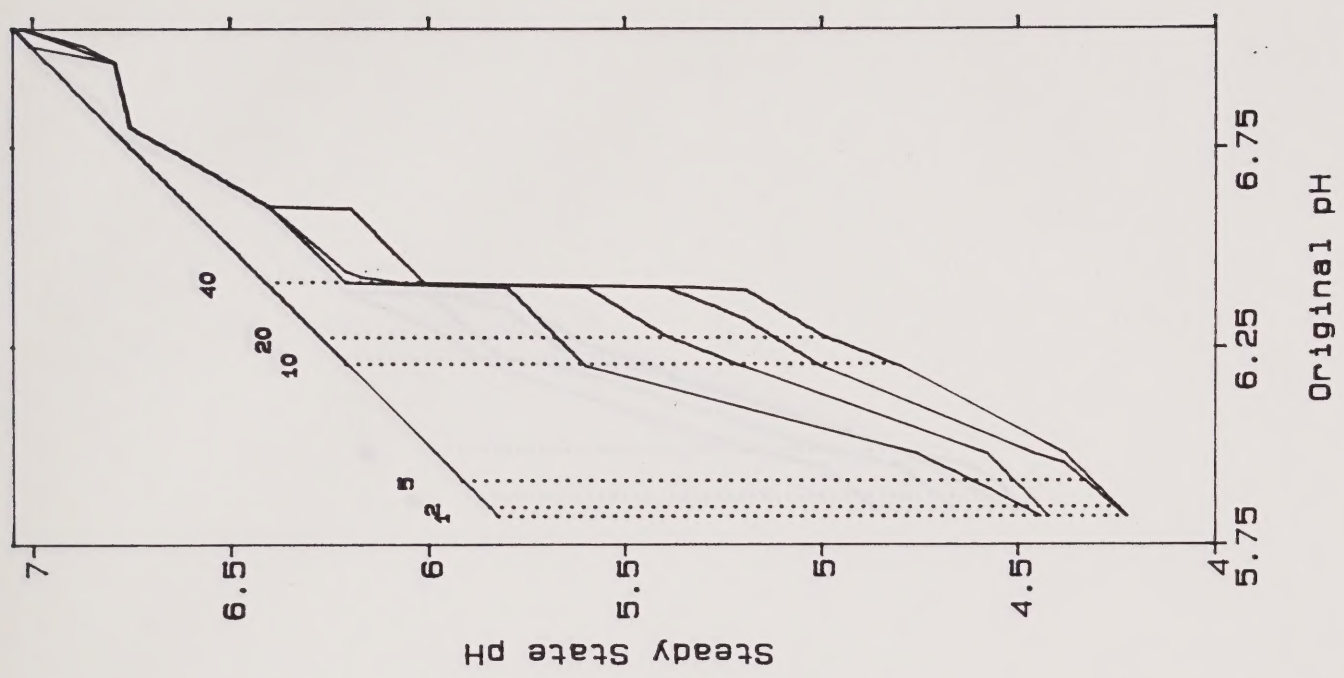
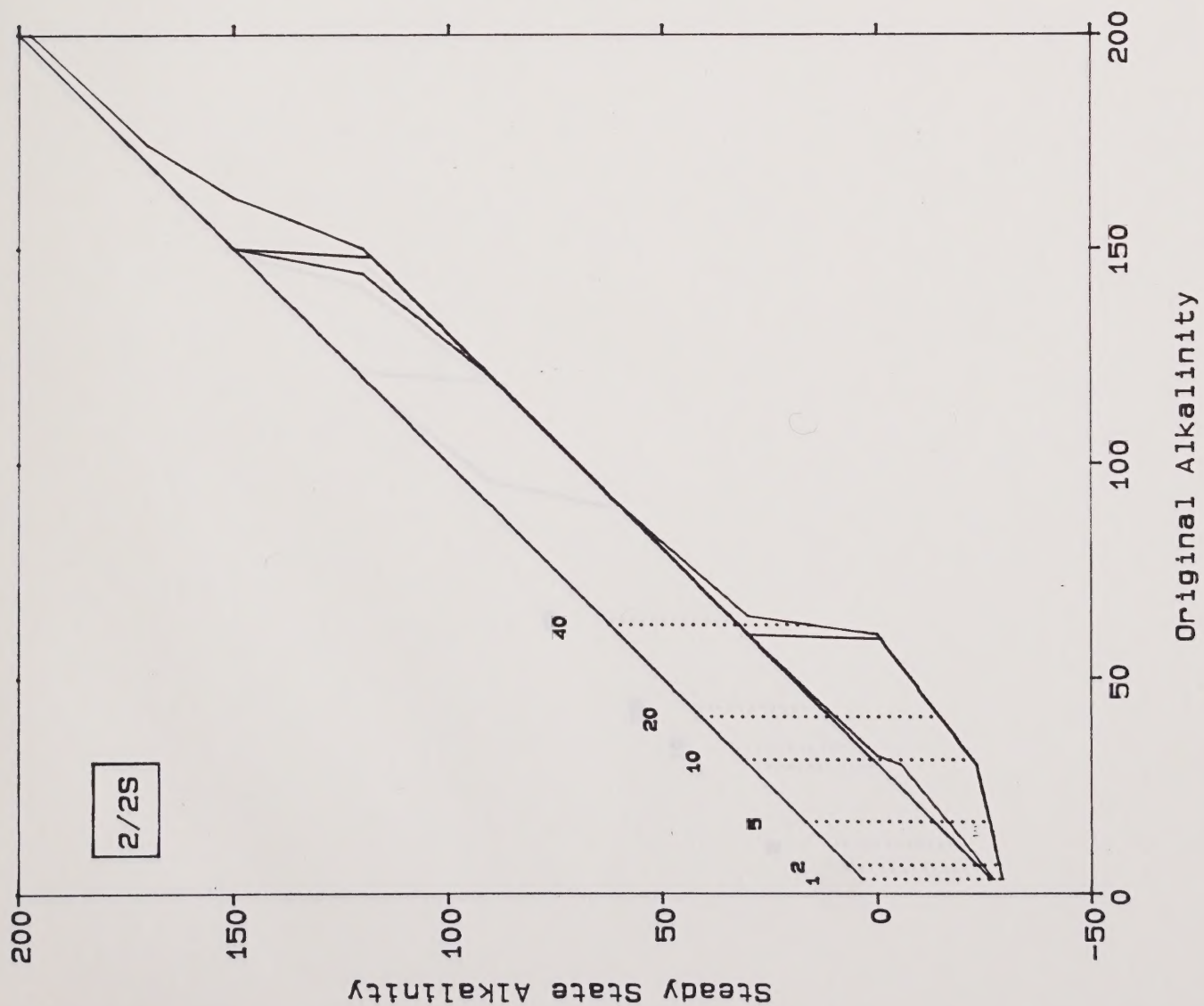


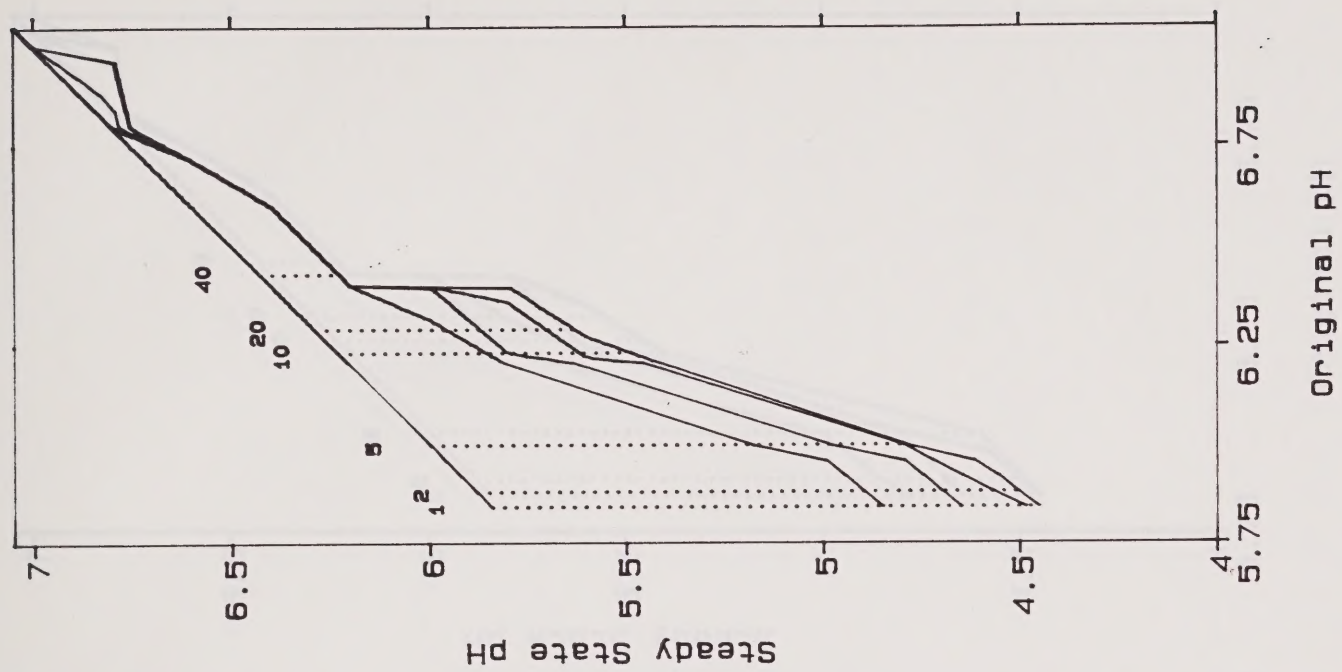
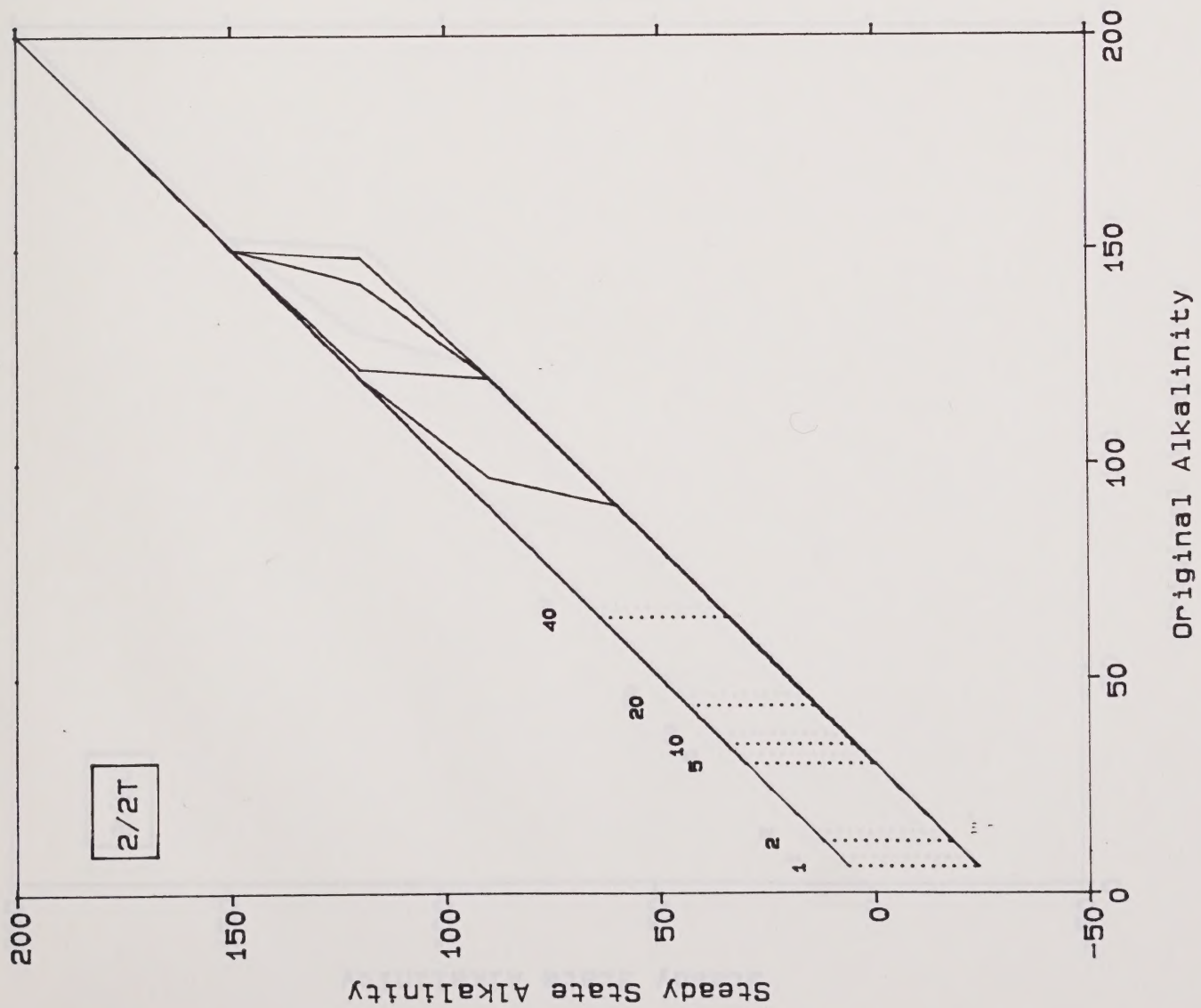


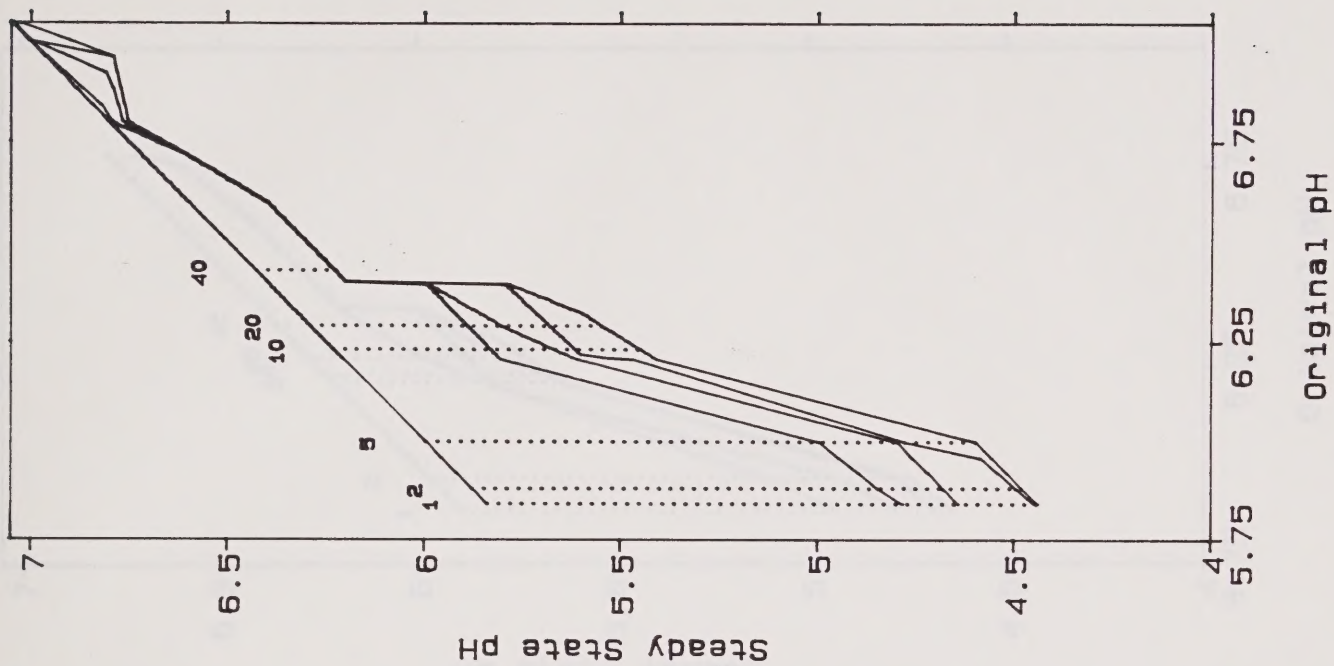
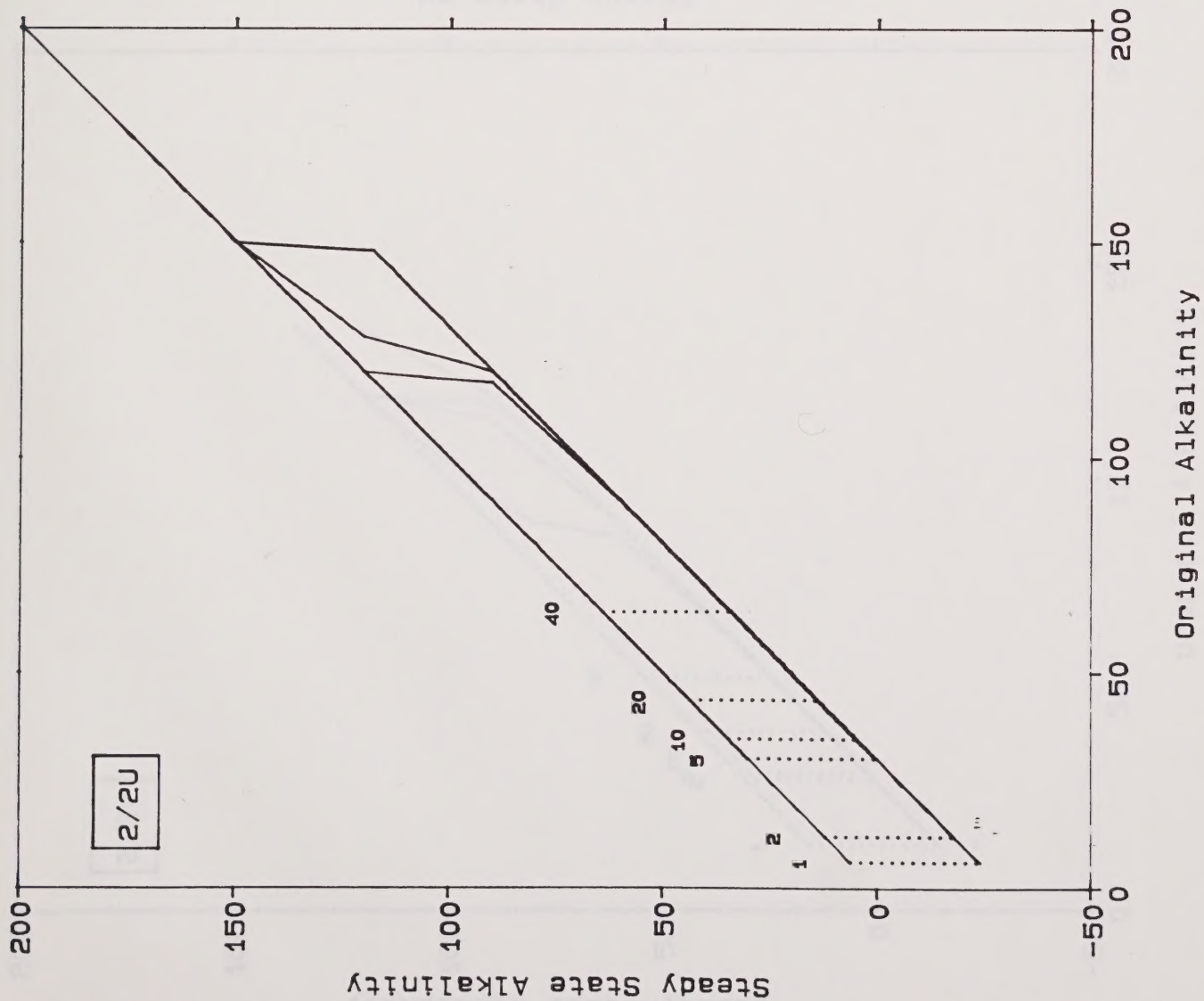


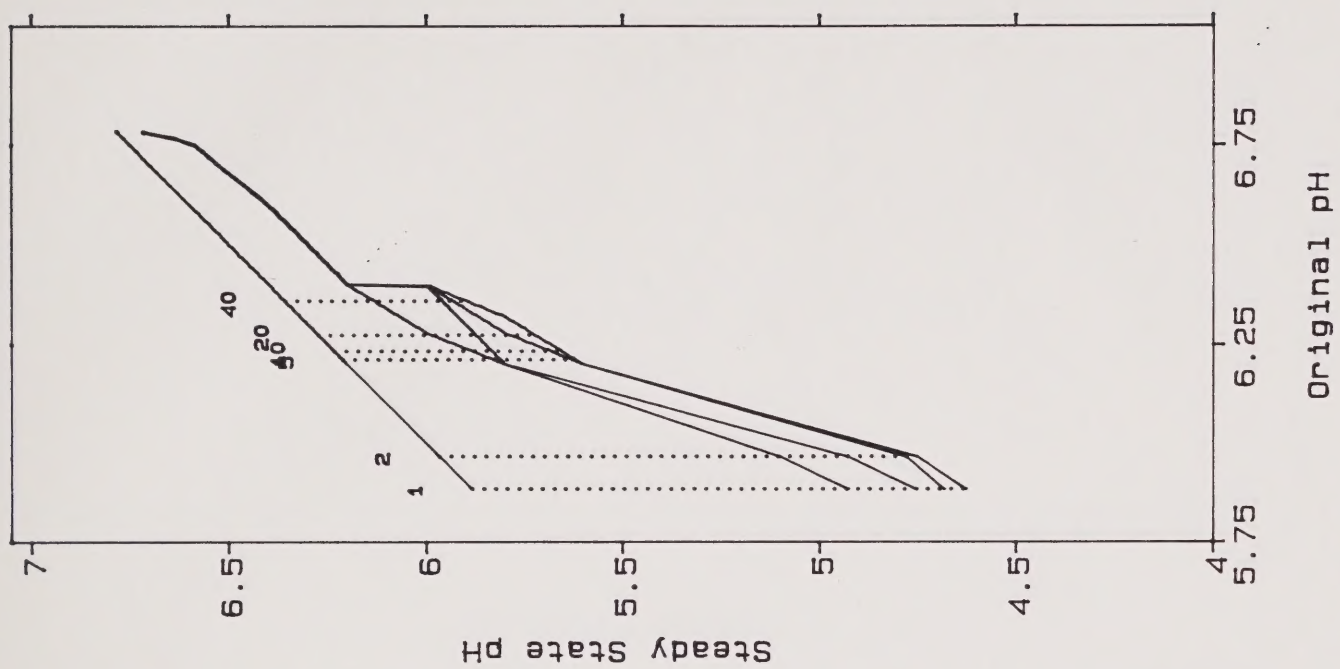
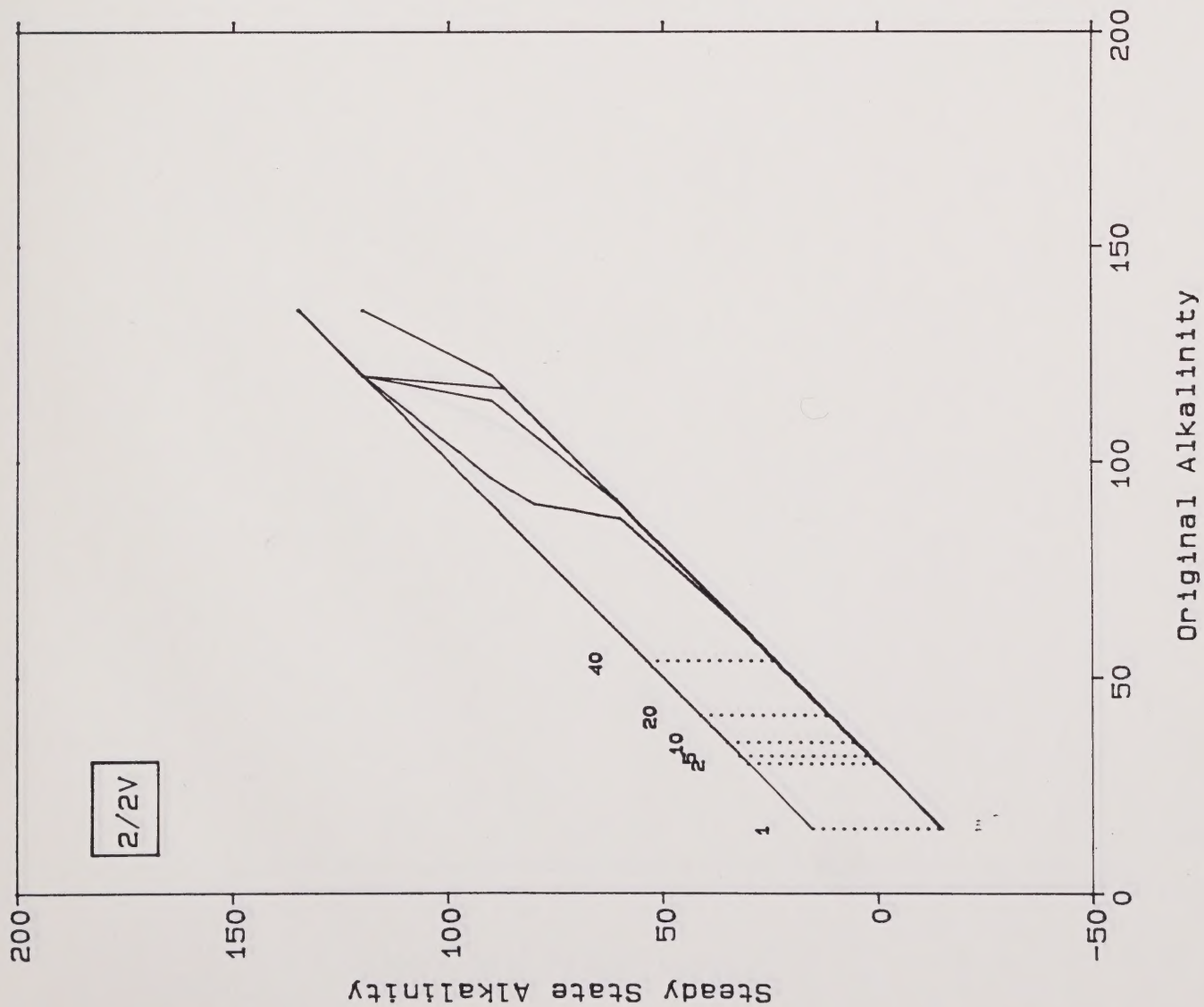


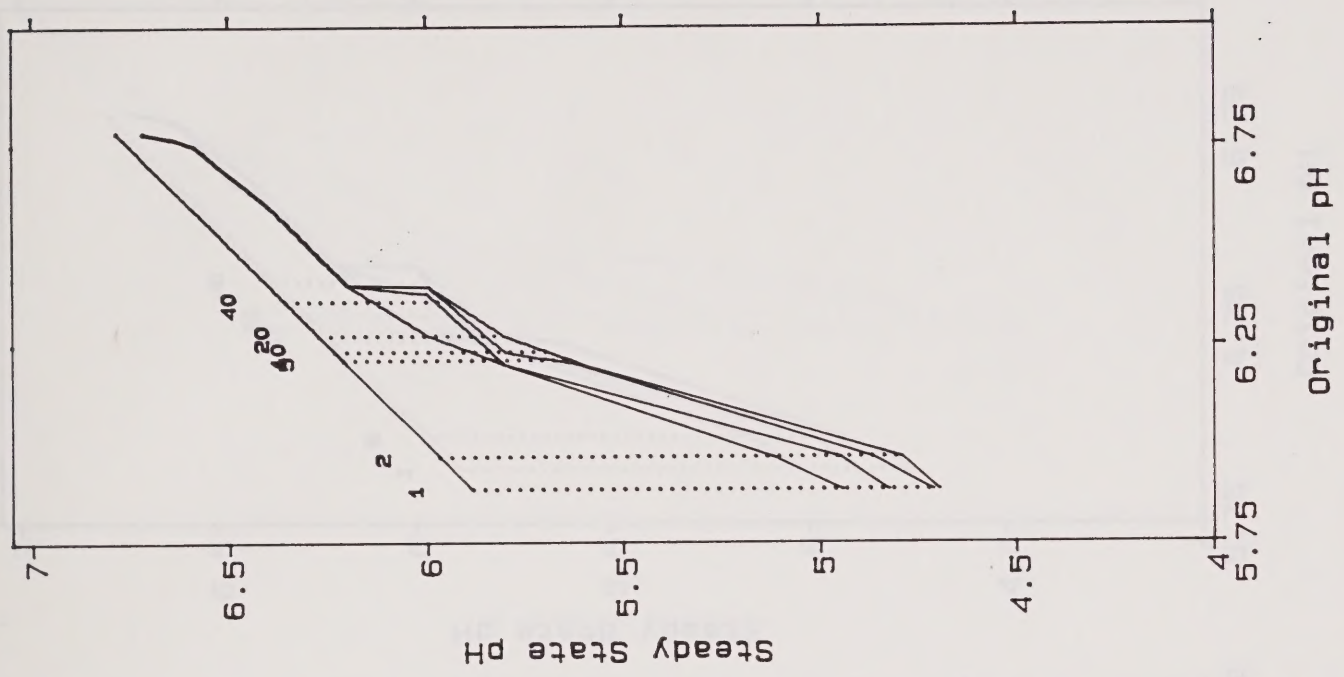
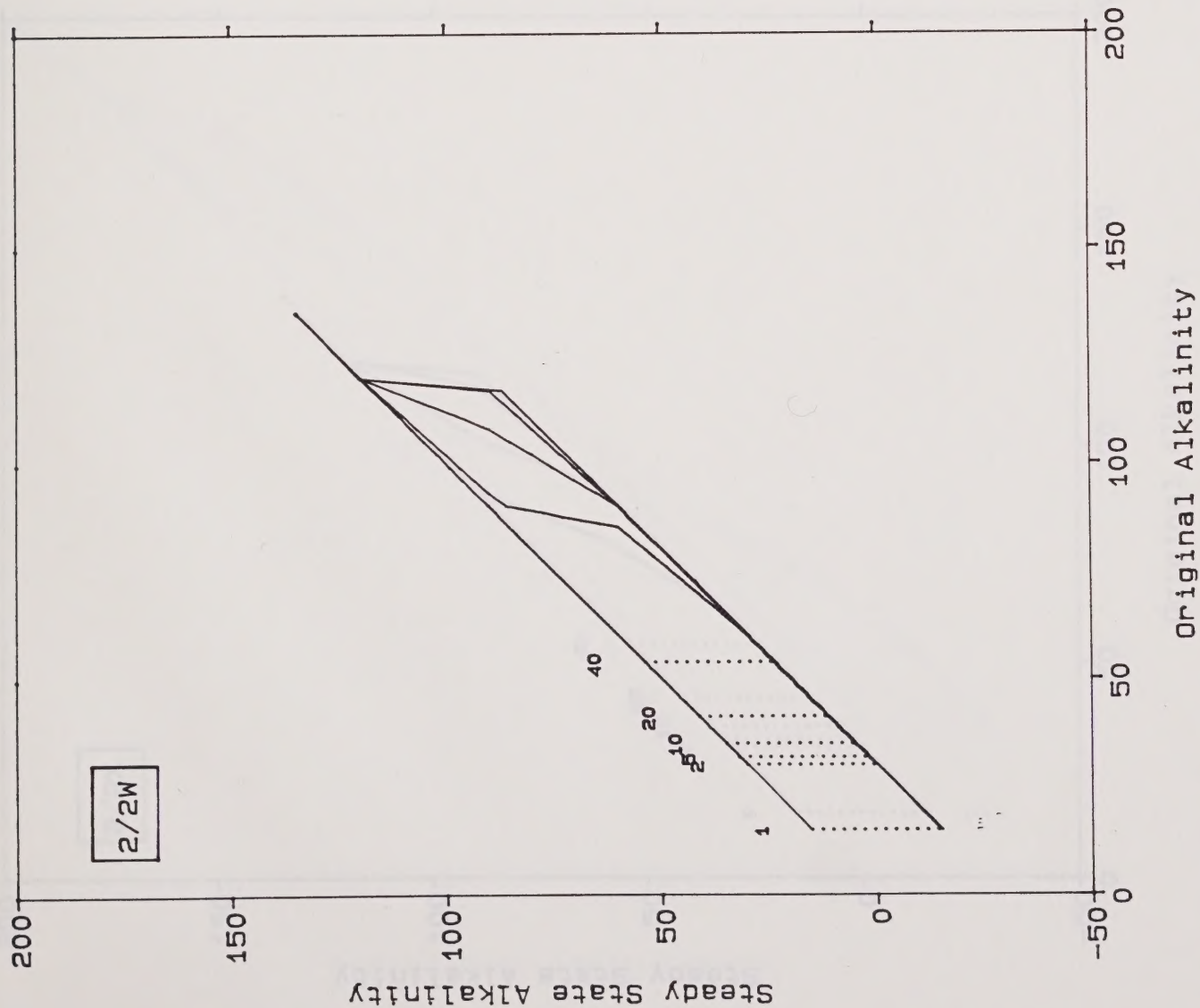


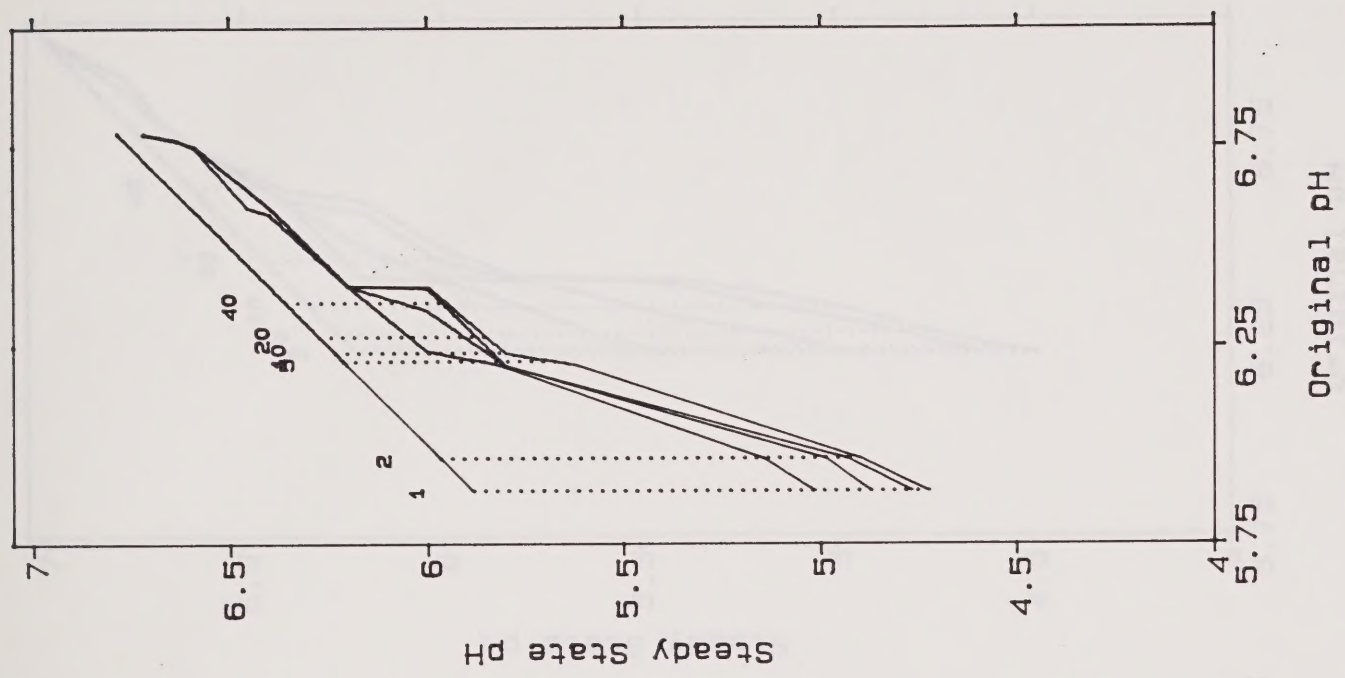
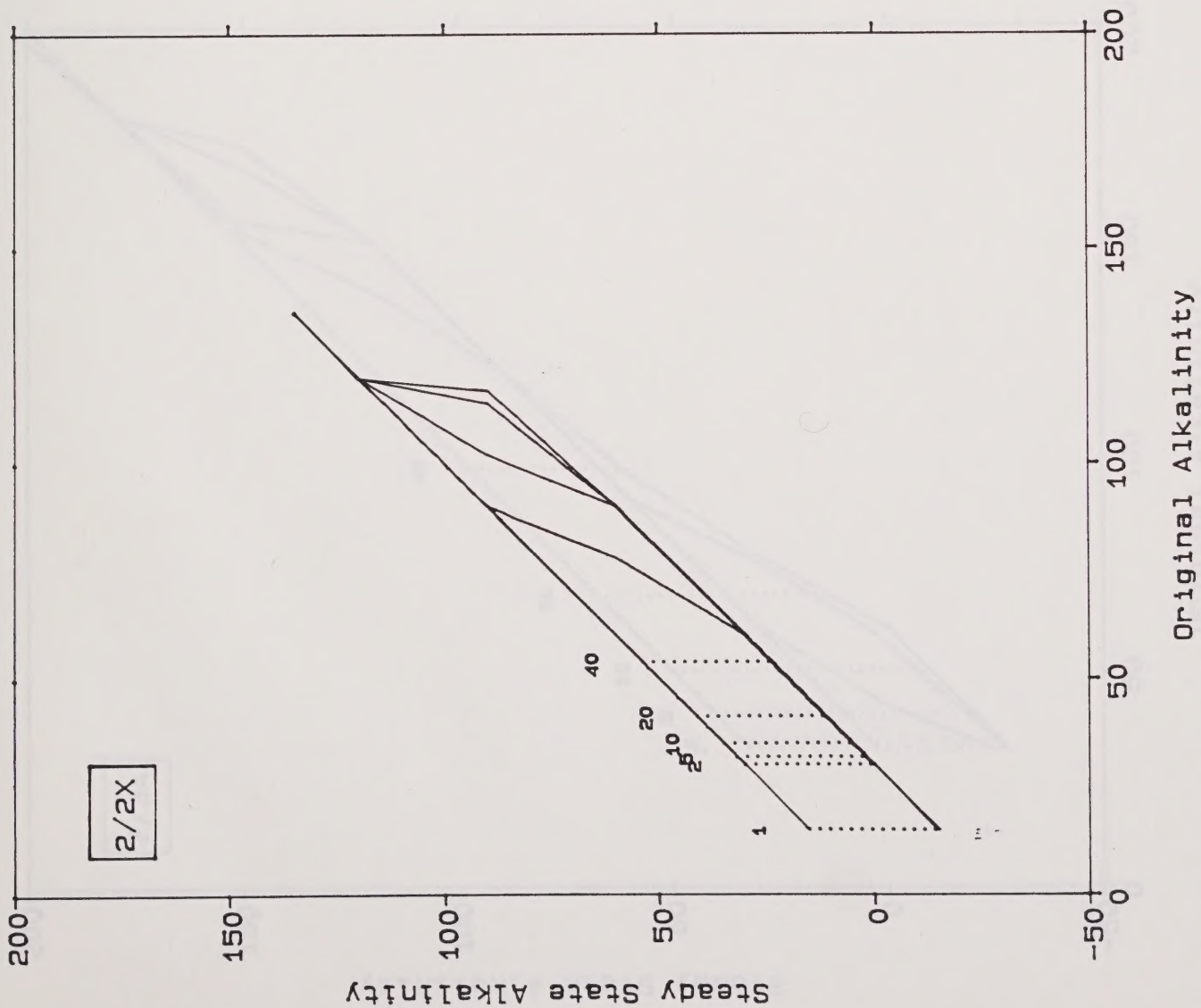


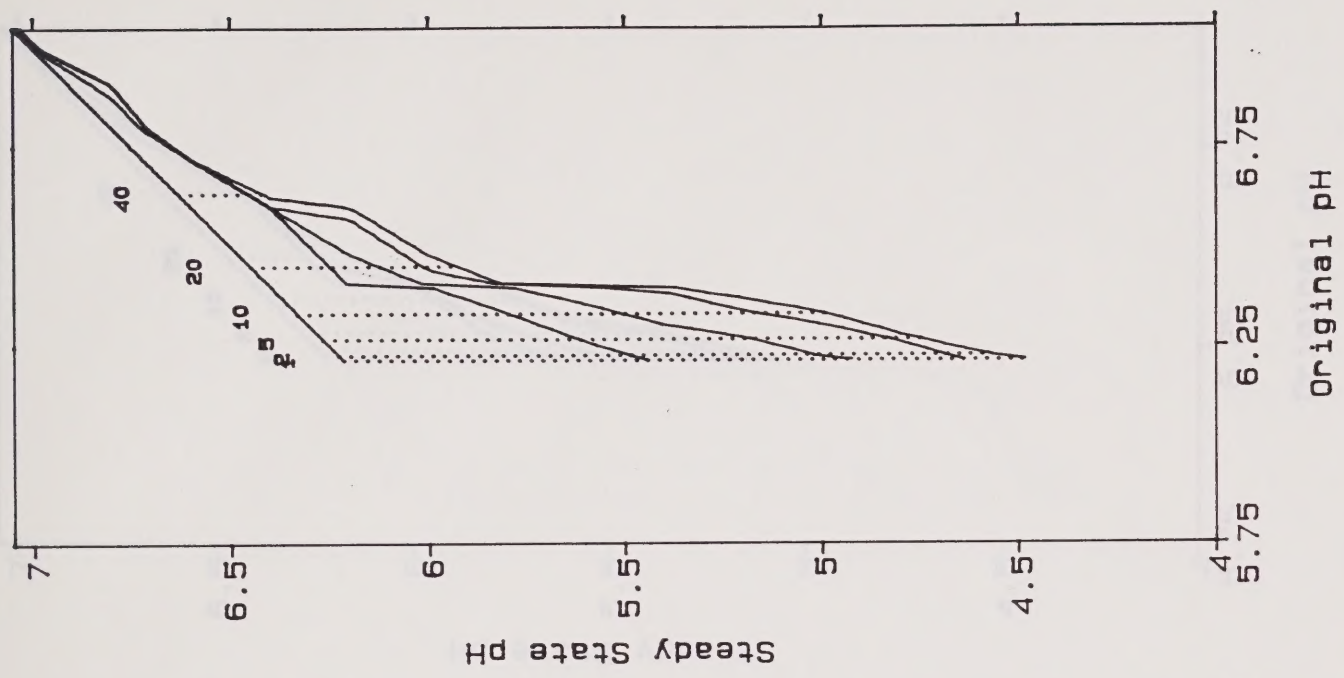
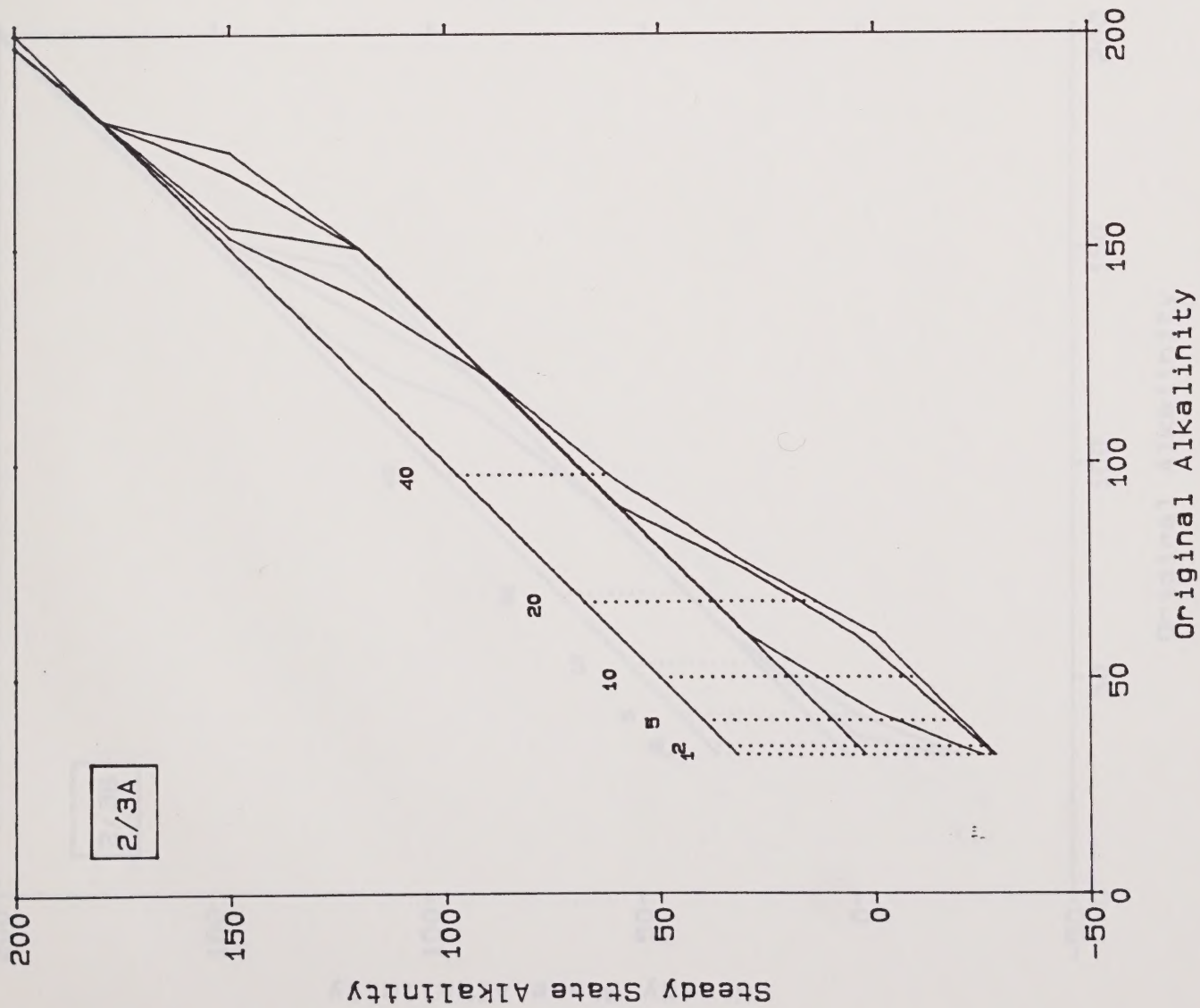


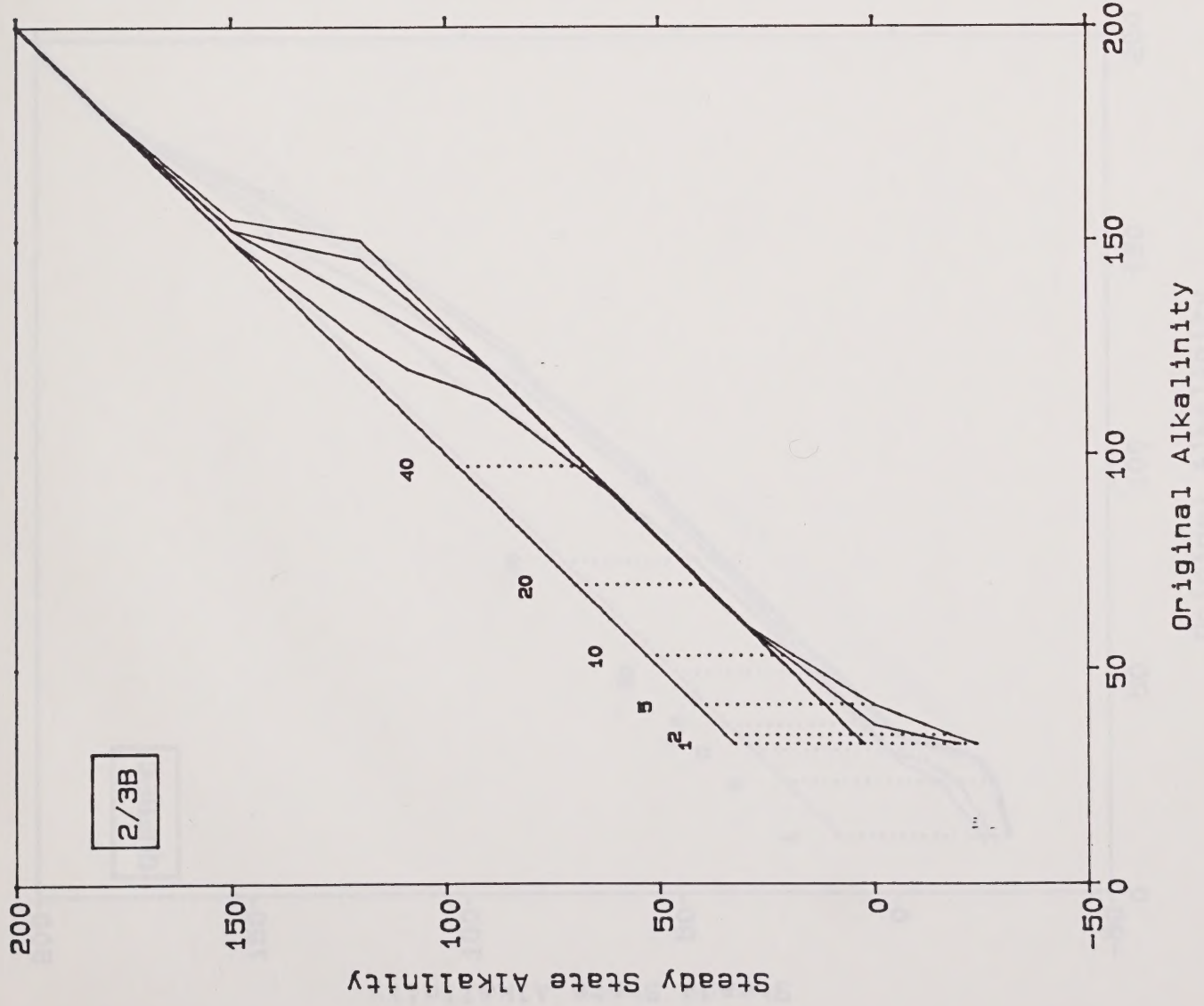
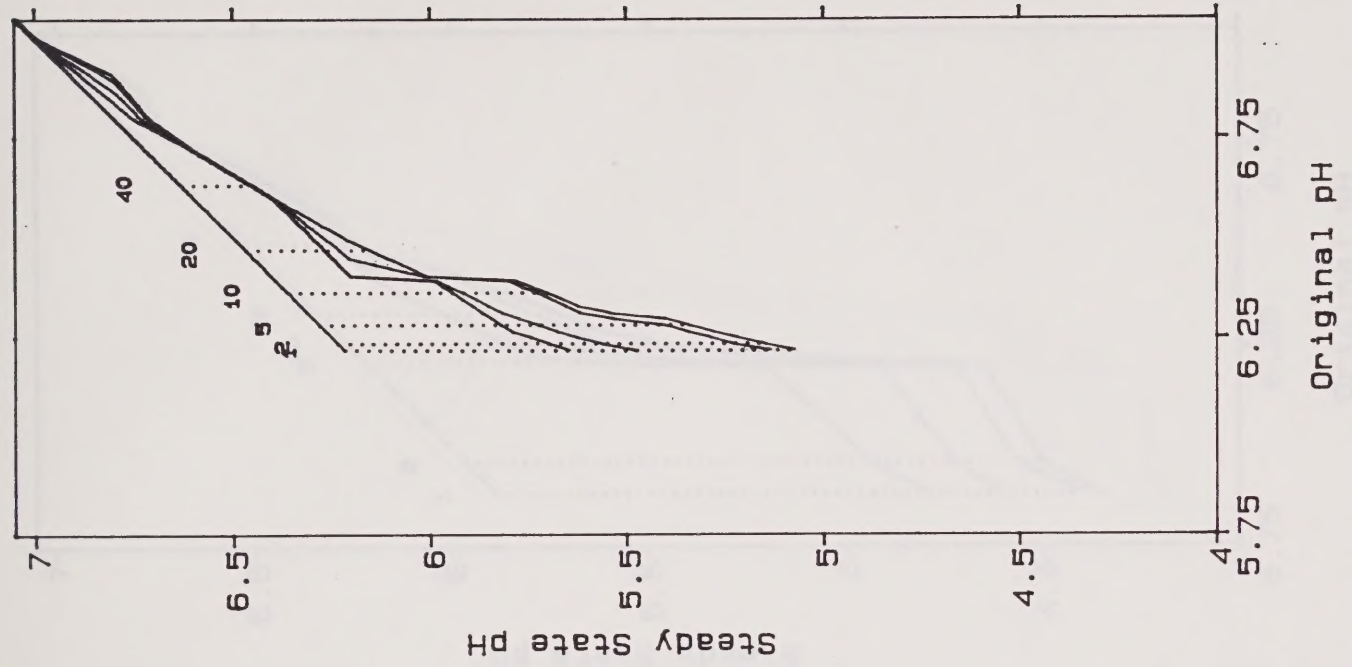












2/3B

